THE UNIVERSITY OF ALBERTA

ELECTRIC ARC FURNACE CONTROL SYSTEM

by

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A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled Electric Arc Furnace Control System submitted by James R. Branson in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

An electric arc furnace control system is studied in this thesis. The stability of the control system is examined and an additional control loop is designed to improve electrode regulation.

The stability of the control system is determined by measuring the time response of the current regulator. Although the system is found to be stable, an improvement in the furnace efficiency is still required. Therefore, an impedance type control is developed which provides both current and voltage feedback. These control signals, along with a reference signal, are applied to the control windings of a magnetic amplifier which controls the conduction angle of a silicon controlled rectifier. The control current to the regulator is varied by the current through the SCR.

The introduction of voltage feedback to the circuit reduces the time and the power required per ton of steel produced. The new control circuit provides control over both the current and voltage, and increases the average power level input.

A considerable saving in production costs and an increase in production is expected with the use of impedance type control.

ACKNOWLEDGEMENTS

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To my wife Joan, my sincere appreciation for her patience and understanding during the preparation of this thesis.

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CHAPTER I

INTRODUCTION

OBJECT

The electric arc furnace is the subject of the project described in this thesis. The objectives are:

1. To improve overall efficiency.
2. To increase refractory life.
3. To improve the stability of the control system.

GENERAL

Use of Electric Arc Furnaces

The electric furnace has replaced the crucible process of making steel and has been established as an effective production tool in the steel industry. The first electric arc furnace in North America was built in 1906. The rated capacity of electric arc furnaces had increased to nearly 10 percent of the annual capacity in the U.S.A. by January 1, 1959. A comparison is made to the rated capacity of other types of steel producing furnaces in Table 1.

TYPE OF FURNACE	RATED CAPACITY Net Tons (Millions)	Percent of Total
Electric Arc	13.5	9.2
Basic Open-Hearth	128.4	87.0
Bessemer	3.6	2.4
Other	2.1	1.4
Total	147.6	100.0

TABLE 1 RATED CAPACITY OF STEEL FURNACES

(U.S.A., January 1, 1959)[1]

Advantages of the electric arc furnace are:[2,3]

1. High heat concentration and quick regulation.
2. High efficiency.
3. High availability.
4. Contamination free melting.
5. Flexibility.
6. Ease of start up and shut down.
7. Close temperature control.
8. Low volume slag which can be adjusted quickly.
9. Ease of tilting furnace to pour off slag.
10. Steel can be treated under any type of slag.

Although there are a few exceptions the electric arc furnace process is based mainly on the use of 100 percent cold scrap. The use of scrap causes the two main

disadvantages of the electric arc furnace:

1. The steel produced contains non-ferrous metal impurities which are in the scrap.
2. The cost per ton of finished material is subject to fluctuations in the scrap market.

Operating costs including labour, power, electrodes, and refractories are usually higher than for the open-hearth and other processes.

The basic electric arc furnace is capable of producing practically all known grades of steel. It is used almost exclusively in the production of steels with an alloy content between 5 and 50 percent. The electric arc furnace is the major producer of stainless, tool, constructional alloy, and special alloy steels. Other products made include: plain-carbon, high-manganese, high-silicon, and aluminum steels; high-speed tool and other alloy tool steels.

Electric Arc Furnace Circuit

The main elements of an electric arc furnace control circuit are shown in Figure 1. Current is carried from the transformer secondary to the mast, through flexible cables, and then through water cooled bus tubes to the electrode. An arc is formed between the electrode

and the furnace charge producing the heat required for melting. The electrode is supported over the furnace by the mast arm. The regulator controls the vertical position of the mast and thus the arc length. The regulator responds to a control signal proportional to the phase current, or to the phase-to-ground voltage and phase current simultaneously. The three phase electric arc furnace is most common, with a separate regulator for each phase.

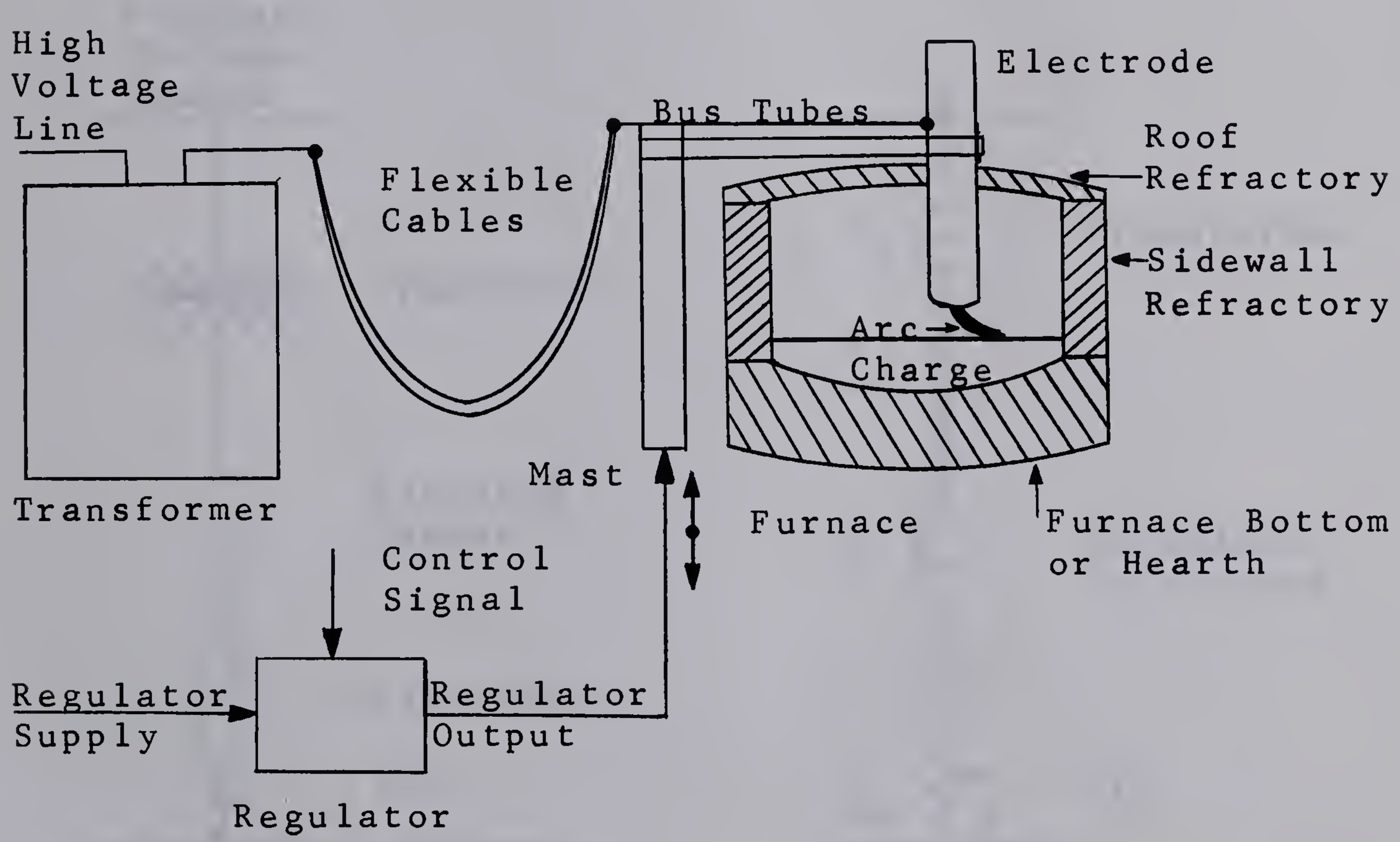
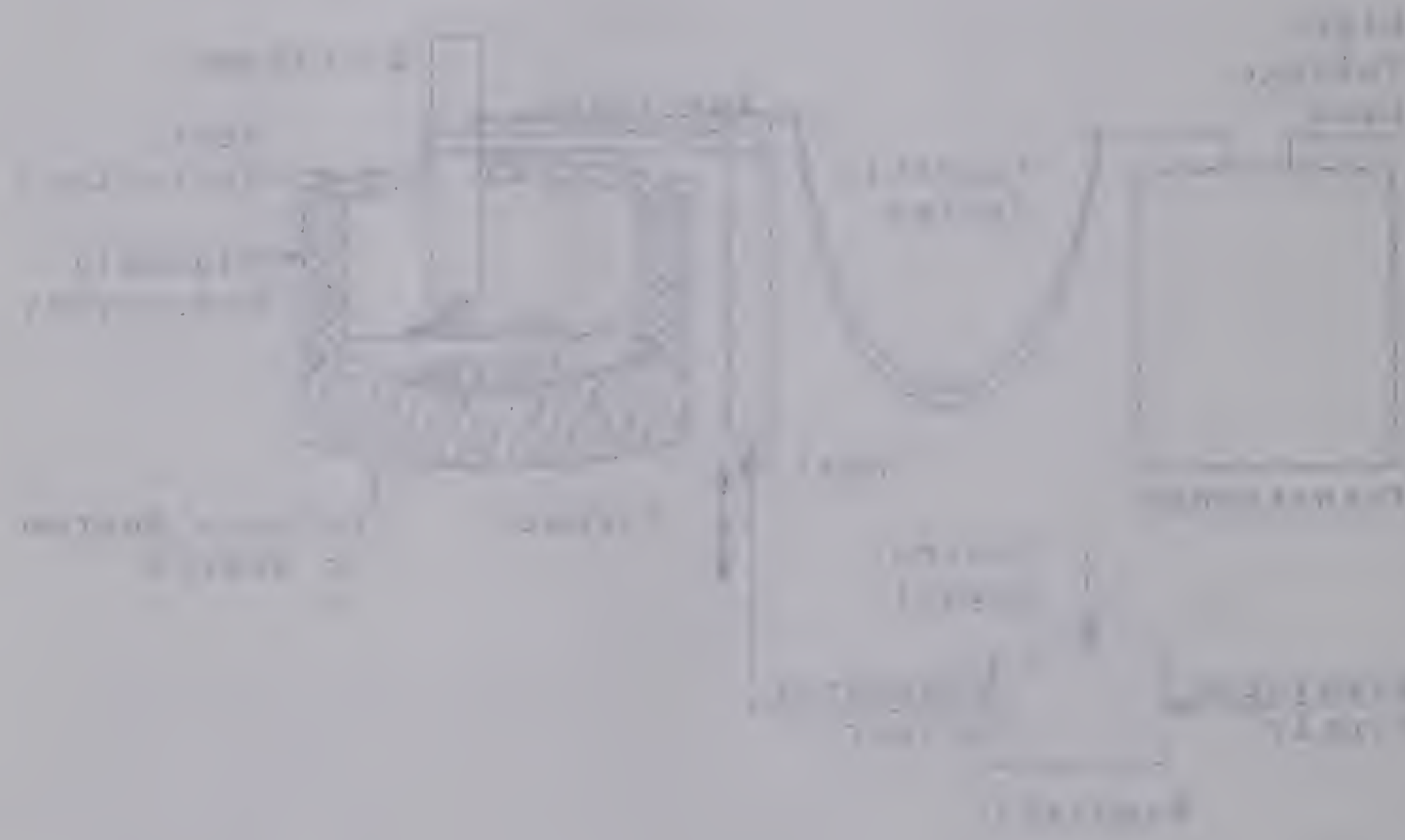
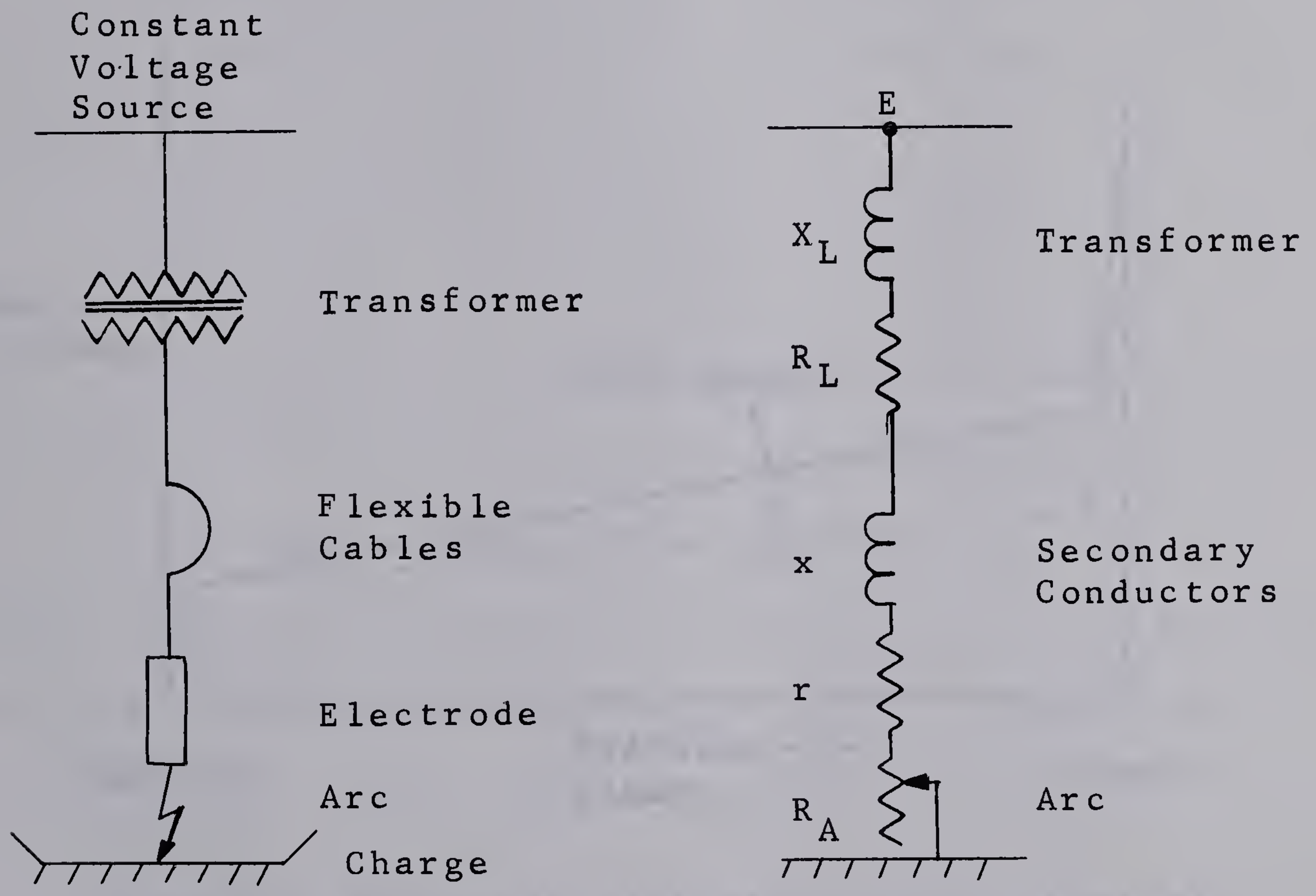


Figure 1 Schematic Diagram of a Typical Electric Arc Furnace Control Circuit



The arc furnace circuit (Figure 2) consists of a constant voltage source, transformer, secondary conductors, electrode, and the arc, represented by a variable resistance, R_A. The arc resistance is varied by the position of the electrode above the charge. Arc resistance and arc voltage are zero when the electrode contacts the charge, resulting in a short circuit current condition. Since this overloads the furnace transformer, the regulator must respond quickly to raise the electrode.



(a) Basic Circuit Diagram (b) Equivalent Circuit Diagram

Figure 2 Fundamental Arc Furnace Circuit

Electric Arc

The electric furnace arc is an extremely powerful source of heat ranging in temperature from 4000 to 5000 degrees Centigrade. The power concentration varies from 500 to 1000 kilowatts per cubic inch.

The electric arc is a discharge between the electrode tip and the surface of the scrap or melt. The voltage distribution between these points, known as hot spots, is shown in Figure 3.(4)

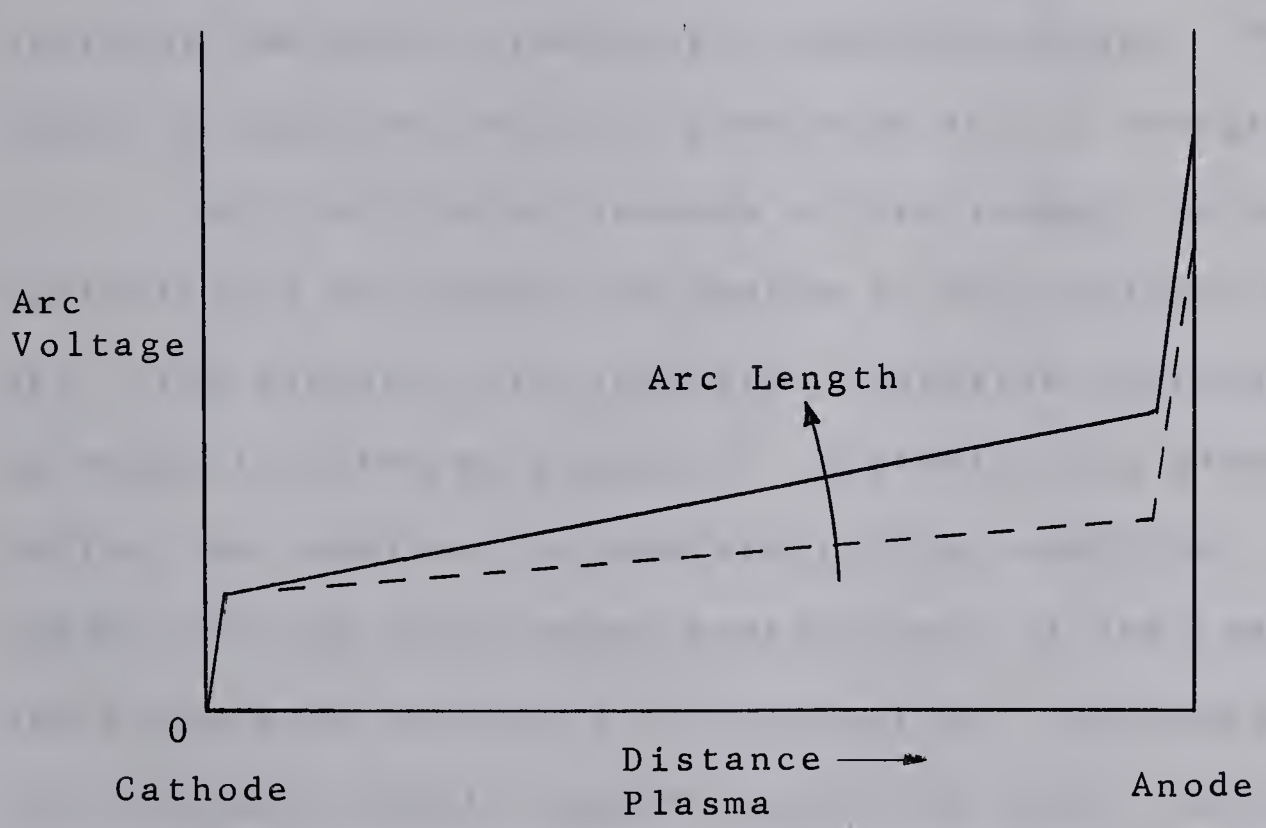


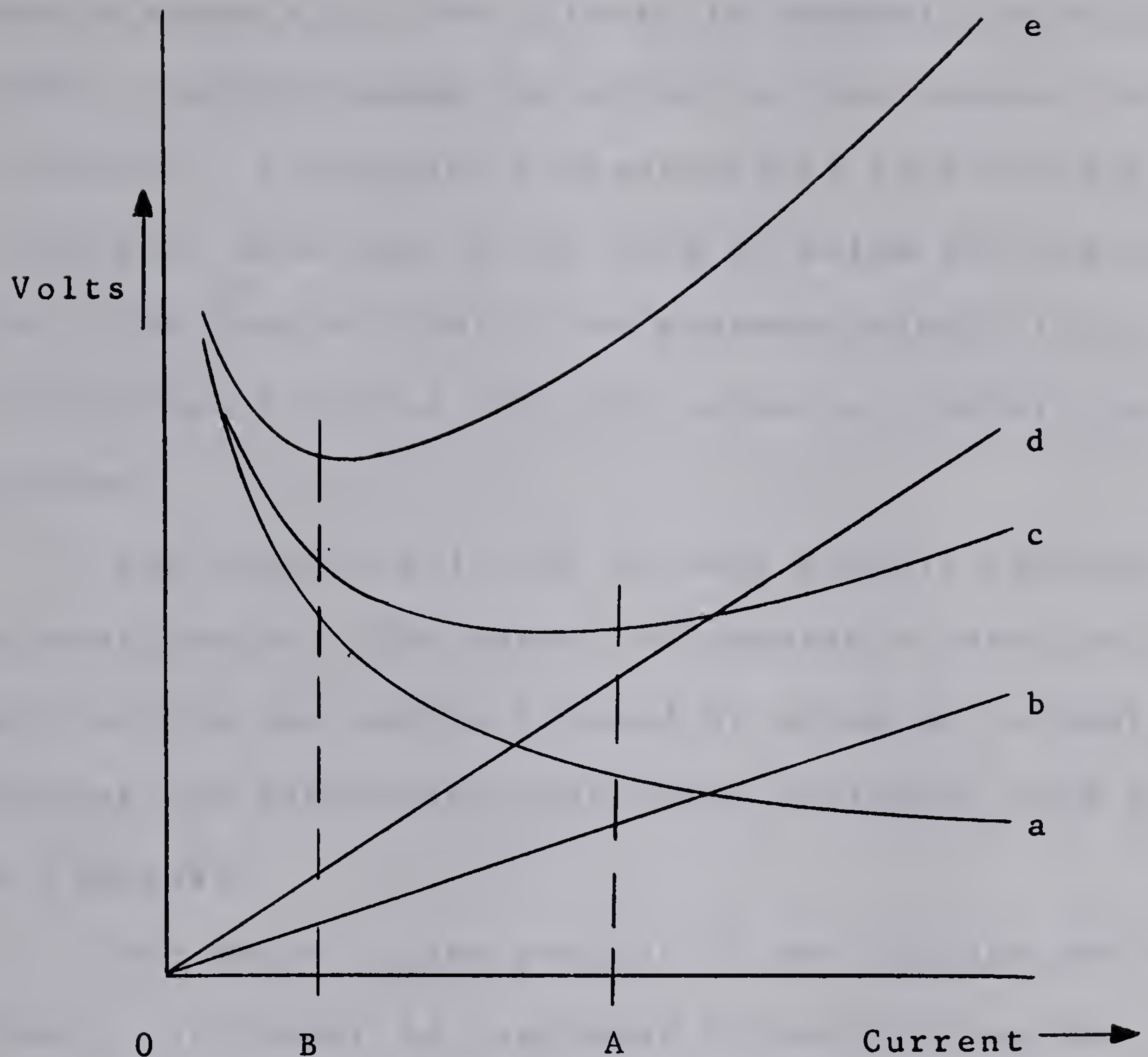
Figure 3 Schematic Distribution of Potential in an Electric Furnace Arc

A crowding of the voltage occurs near the two hot spots. Heat is radiated from the electrode hot spot onto the charge below, while the hot spot on the metal surface receives heat which is conducted further into the melt. The arc column between the hot spots radiates heat onto the melt and into the surrounding scrap. When most of the scrap is melted, leaving the sidewalls bare, part of the heat is absorbed by the sidewall and roof refractory.

Mechanical forces are generated by the arc striking the melt, producing a stirring action. This helps to equalize the heat generated in the charge.

Arc resistance depends on arc length and conductivity of the gases and vapors in the vicinity of the arc. The electric arc exhibits a negative characteristic as shown in Curve a, Figure 4. A stabilizing element or ballast is required to counteract this condition. The conductors and transformer provide part of the reactance and resistance necessary for ballast but supplementary reactors are usually needed except for large transformers. The reactor is added in series with the primary winding of the transformer.

The secondary reactance produces a positive volt-ampere characteristic (Curve c, Figure 4) for



Volt-Ampere Characteristics

Curve a) Arc

b) Secondary Reactance

c) Curve a + Curve b

d) Supplementary Reactance

e) Curve d + Curve c

Figure 4 Volt-Ampere Characteristic of the Arc and the Effect of Reactance in the Circuit

currents above A but the circuit is unstable below this current. Curve e shows the effect of the reactor in the circuit. A negative characteristic is still present for currents less than B but this is below the operating range. The reactor limits the maximum current in one direction and prevents the destruction of the arc in the other.

Any reactance in the furnace circuit reduces the power factor. The amount of reactance required to stabilize the arc can be reduced by using an automatic regulator and electrode positioning equipment with a fast response.

Arc power is the product of arc voltage and arc current. Arc power is regulated by controlling the secondary voltage of the transformer and positioning the electrode above the charge. A tap changer on the transformer selects the operating voltage and arc current is adjusted by automatic regulators.

The electrode position and thus the arc length are controlled by setting the rheostat of the regulator. A low arc, high cuurent, has most of its heat focused under the electrode tip. A more horizontal heat radiation pattern is produced by a high arc. Figure 5 shows

that arc length and the gap between the electrode and the melt are different.[5]

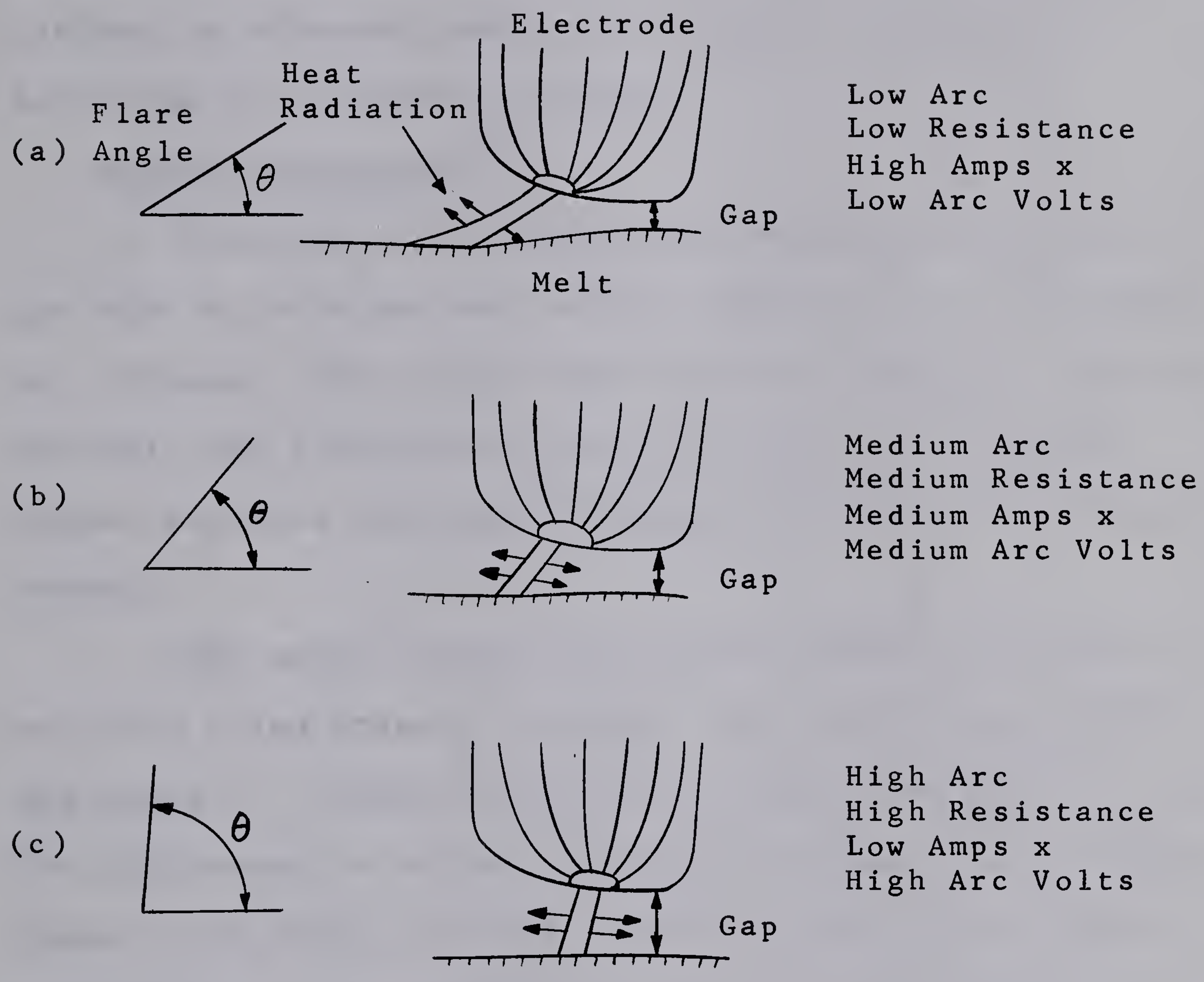


Figure 5 Electrode and Arc Positions

Strong magnetic fields, present in the vicinity of the arc, together with the force of the arc striking the melt, create an erratic turbulent condition near the arc. Changes in the arc gap and arc length occur,

producing changes in arc current and arc power. Electrode regulators can only partially control the effects of these forces. Arc flare, produced by the magnetic fields, is directed toward the furnace sidewalls contributing to refractory erosion.

Mutual Inductance[3]

The high current carrying conductors are arranged side by side and are equally spaced in a conventional arc furnace. Due to the high currents flowing in the conductors, the difference in mutual inductance between phases produces considerable power unbalance at the electrodes.

The mutual inductance between phase 1 and phase 2 or phase 2 and phase 3 is larger than that between phase 1 and phase 3. Assume an electrical phase sequence of 1-2-3. The difference in mutual inductance between phase 2 versus phase 1 and phase 3 versus phase 1, induces a voltage in opposition to the current in phase 1. This counter emf increases the effective resistance of phase 1. Phase 3 receives an induced voltage, in phase with the current, reducing its effective resistance. This results in the leading phase (1) delivering less power and the lagging phase (3) more. The center phase is relatively unaffected by the mutual inductance since the outer phases induce

equal and opposite voltages in the center conductors. On furnaces where the center electrode is nearest the transformer, the most power is delivered by the center phase because the secondary conductors are shorter resulting in lower self inductance and resistance. The effects of mutual inductance are shown in Figure 6 for a furnace with phase rotation of C-B-A.

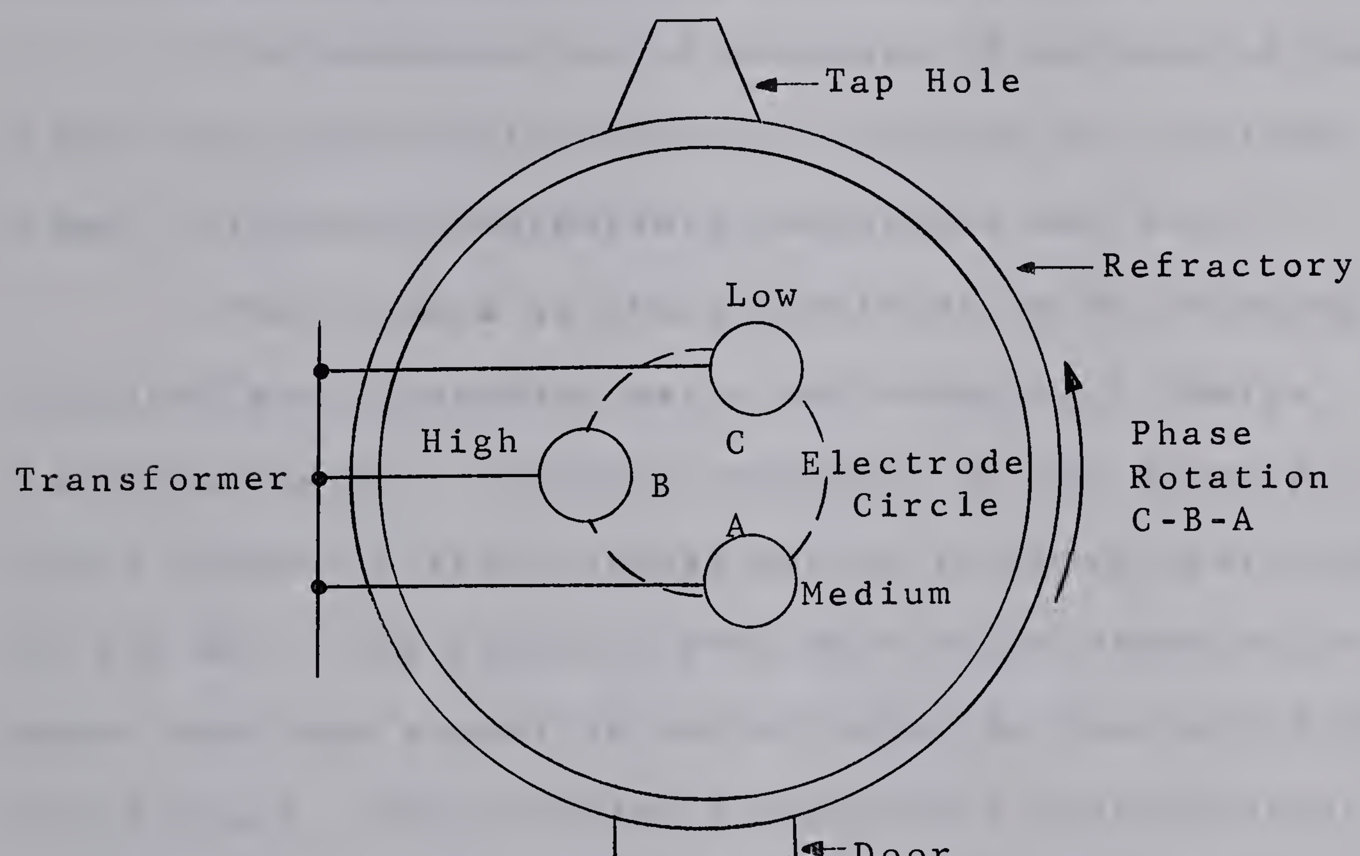


Figure 6 Effect of Mutual Inductance on Arc Power

Unequal heating is produced in the furnace resulting in the greatest refractory erosion behind the center phase. The sidewalls are protected by scrap during the initial stages of melt down but refractory erosion increases as the refining period is approached.

Furnace Operation

The amount of steel produced at one time is called a "heat." The time required to produce a heat consists of the meltdown and refining periods.

The meltdown period averages 70 percent of the total time and requires about 75 percent of the total power, although considerable variations may occur.

The furnace is charged with scrap by swinging the roof and electrodes aside and dropping a charge into the furnace. Initial breakdown of the scrap produces violent current swings due to repeated restriking of the arc. The electric arcs melt holes through the scrap and form a pool of molten metal in the bottom of the furnace. Scrap falls in around the electrodes as the molten pool enlarges. With most of the scrap melted, recharging takes place and the cycle is repeated.

The final stage of meltdown, the flat-bath period, starts when the final charge is nearly melted. Maximum power is required to melt the remaining scrap

and to increase the temperature. This portion of the heat produces maximum refractory erosion through thermal, physical, and chemical attack.[4]

The lower power input necessary during the refining period is obtained by operating at lower voltages and reduced current. Test samples taken from the melt are analyzed in the lab. Adjustments are then made by adding reagents and more samples are taken. Slag, formed to remove impurities, is poured into a slag pot. Temperature measurements are obtained by inserting a disposable thermocouple in the melt. When the melt reaches the desired temperature and composition the heat is ready for casting. The finished heat is poured from the furnace into a ladle.

ELECTRODE REGULATION

Transformer Secondary

Power to the electric furnace described in this thesis is supplied by a transformer with an ungrounded-star secondary connection as shown in Figure 7. Under stable operating conditions, the neutral point shifts slightly with respect to ground due to unbalanced loading as shown in Figure 7(b).

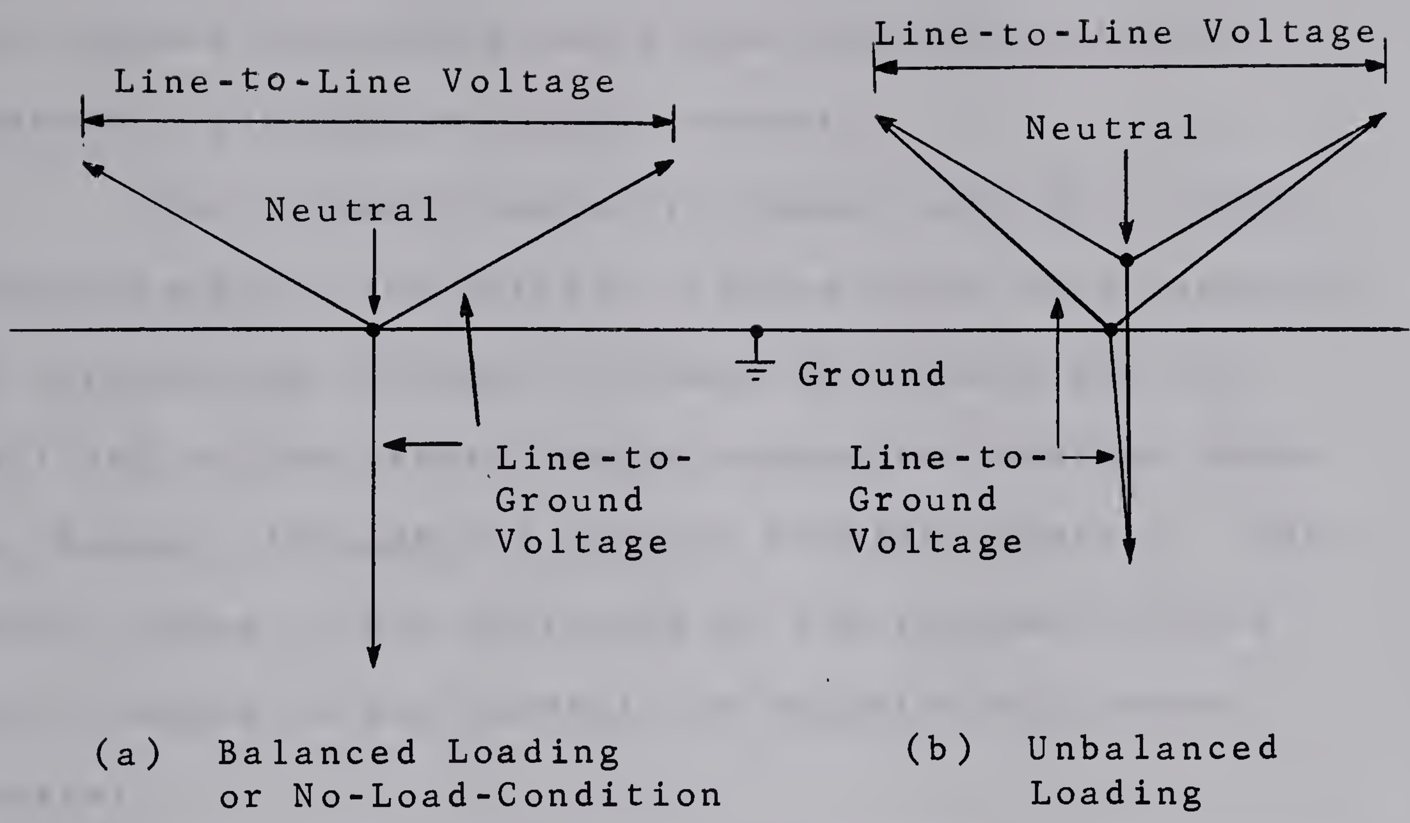


Figure 7 Effect of Unbalanced Loading on Secondary Voltages

The neutral point may shift even further from ground potential as the arc fluctuates producing greater unbalance between phases. The line to ground voltages change as the neutral point shifts. A change of voltage in any phase causes a voltage change in the other phases. Power is also affected since it is a function of voltage.

Electrode Regulators

The purpose of the electrode regulator is to provide a constant power input to the furnace which is achieved only if the regulator senses all power changes.

Arc furnace regulators use either current control or impedance (difference) type control.

The current regulators depend only on a signal proportional to arc current. Since power is a function of current and voltage, a change in voltage due to shifting of the neutral point causes the average power to change, although the current remains constant. This power change is not corrected by the regulator since only changes in arc current are detected by current control.

Impedance type control is based on the difference between a current and a voltage signal. A reference signal is necessary to provide a control signal when the error signal is zero. The regulation equation is

$$V_c = V_r + aK_1 I_a - bK_2 \frac{V}{V_t}$$

and the error equation is

$$V_e = aK_1 I_a - bK_2 \frac{V}{V_t}$$

where V_c is the control signal

V_r is the reference signal

V_e is the error signal

I_a is arc current

V is secondary voltage

V_t is open-circuit voltage and varies with changes in the tap voltage

a and b are constants

K_1 varies with the setting of the control rheostat

K_2 is constant but may be adjusted to provide a change in the current range

When the error signal is zero

$$V_c = V_r$$

and

$$\frac{V}{I_a} = \frac{aK_1V_t}{bK_2} = Z$$

where Z is the impedance.

For any given current and voltage, the impedance is constant. The control rheostat is adjusted to some preset current with a corresponding voltage. The regulator attempts to keep the current and voltage constant, thus keeping the impedance constant.

The impedance determined from the error equation is that of the arc, and that portion of the secondary circuit between the arc and the point of voltage measurement. If the voltage were measured at the arc, the impedance Z would be arc resistance only. However, it is impossible to measure arc voltage due to the extreme heat generated by the arc. When the voltage is measured at the

electrode holder or on the transformer secondary bus, the impedance expression includes a reactive component. The voltage signal obtained from the electrode holder is much more sensitive to changes in the arc since the high reactance of the secondary conductors is not included.

The main advantage of impedance type regulators is that the impedance of each arc is not influenced by the conditions of the other two phases. This permits an essentially separate regulation for each electrode with greater stability and precision.[6] Since the impedance of each arc is independent of the other phases the power must also be independent. Therefore, the impedance regulator is capable of keeping an almost constant flow of power to the furnace.

CHAPTER II

CURRENT CONTROL

FURNACE DESCRIPTION

Furnace Control Circuit

The specifications for the electric arc furnace examined in this project are given in Appendix I. Figure 8 shows the control circuit. The regulator receives an electrical control signal which controls the position of a hydraulic valve. The flow of hydraulic fluid to the electrode raising cylinder is controlled by the valve position.

Arc current is the only variable used to regulate the electrode position. However, a differential voltage signal is provided to override the current signal when the arc voltage is reduced to zero. Provision is made to change the secondary voltage while the transformer is de-energized.

Regulator Description

The regulator consists of three control units, one for each phase, mounted at the base of an oil tank. The upper part of each unit, inside the tank, is the servo mechanism. The lower portion, below the tank, is a piston type hydraulic valve which controls the flow of hydraulic

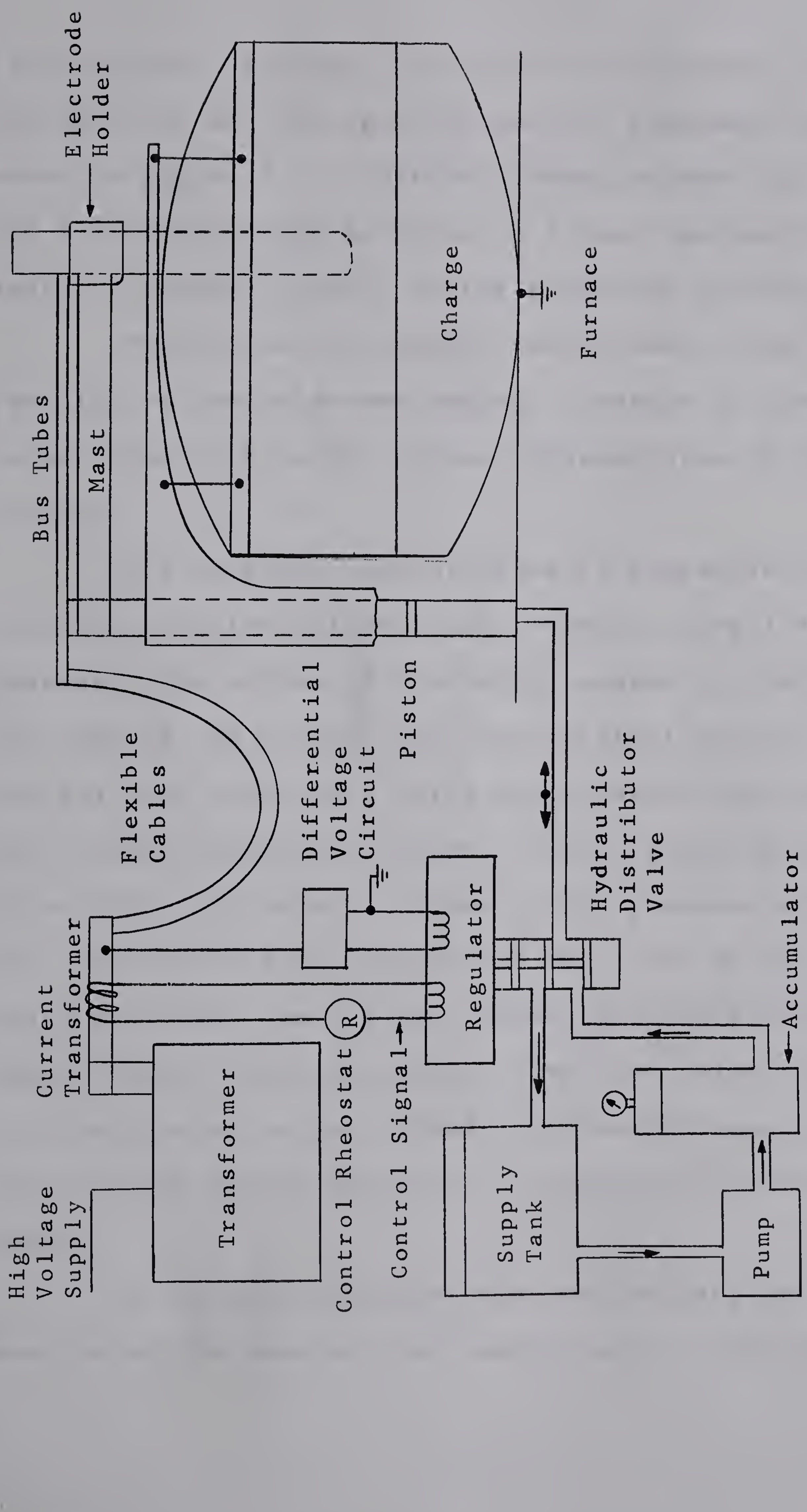
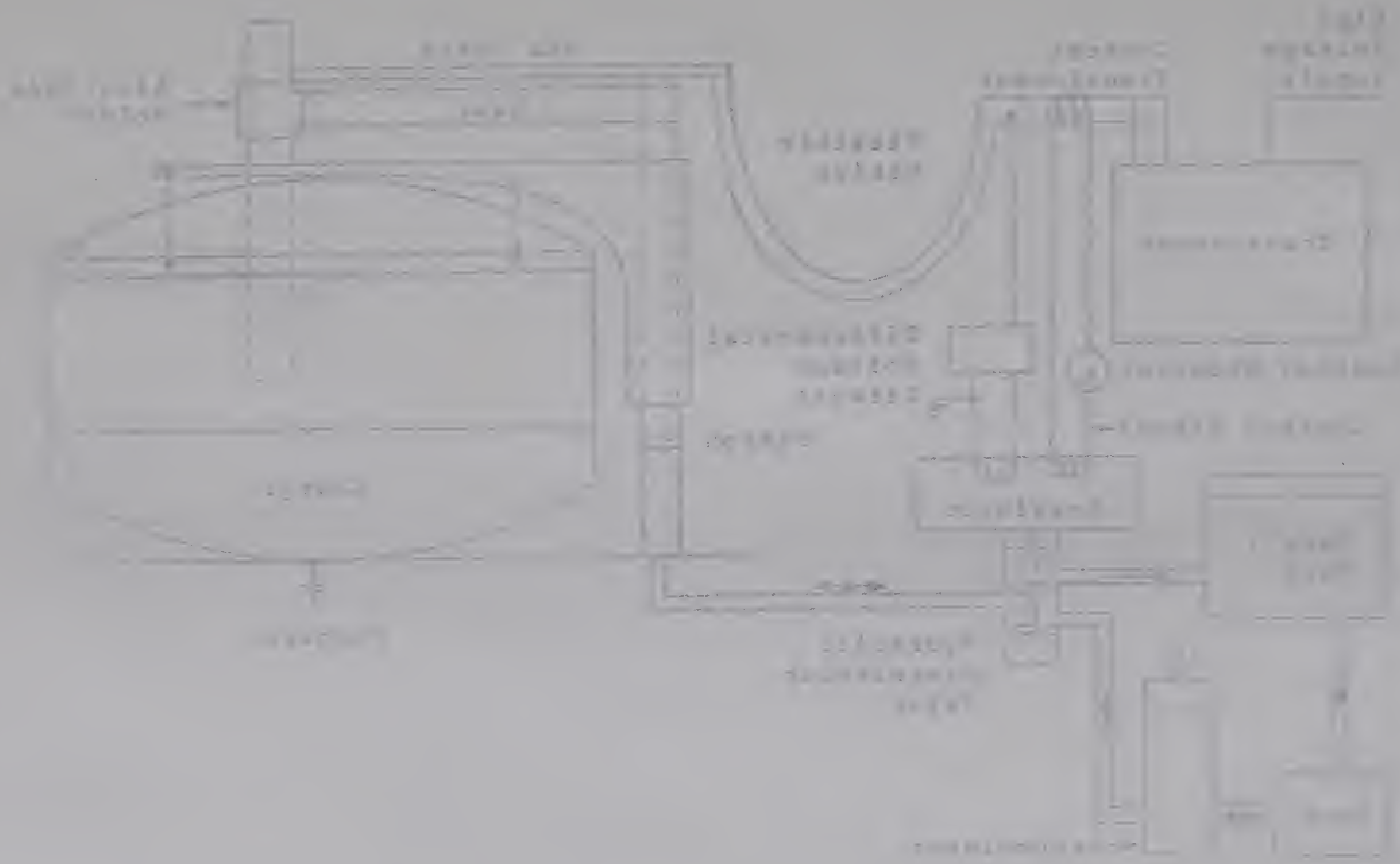


Figure 8 Furnace Control Circuit with Electro-Hydraulic Regulator



fluid to the electrode cylinders on the furnace. A cutaway view of the regulator and its component parts is shown in Figure 9. A stirrup located between the top and bottom parts can be moved by a hand operated control lever for manual control of the electrode position.

The piston is normally restrained in the down position by the hold-down spring. Tension of the spring is adjusted by a collar on the threaded stem of the piston.

The rotating control valve is supported at the top by a circular collar which contains a small needle bearing. The bottom of the valve, seated in the hollowed out head of the piston, has four vertical slots. The piston has four horizontal holes which extend into the pressure chamber below the piston. Oil is supplied by a pump, through the oil control valves to the pressure chamber. When the holes in the piston and the slots in the control valve coincide, the oil is released and the hold-down spring forces the piston down. When the valve closes (the slots and holes are not lined up), the oil pressure builds up under the piston forcing it up against the force of the spring.

A laminated armature with restraining springs is mounted on the stem of the control valve. The opposite ends

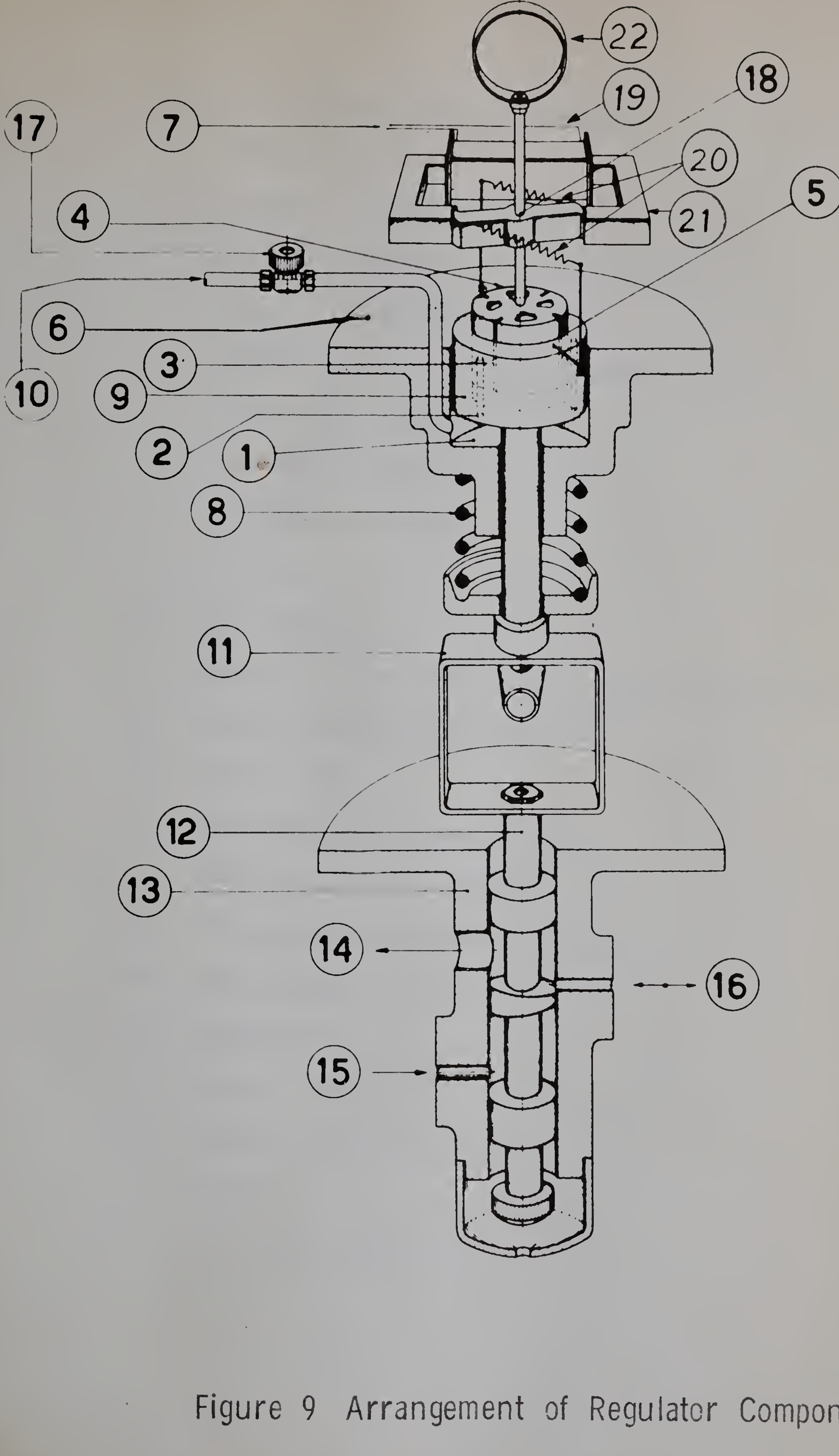


Figure 9 Arrangement of Regulator Components

Regulator Components

1. Pressure chamber.
2. Vertical holes in the piston.
3. Horizontal holes in the piston.
4. Rotating control valve.
5. Vertical slots in the control valve.
6. Bronze cylinder.
7. Control signal.
8. Hold-down spring.
9. Piston.
10. Oil supply.
11. Stirrup connecting piston and distributor valve.
12. Hydraulic distributor valve.
13. Cast block.
14. Discharge to supply tank.
15. Hydraulic fluid supply.
16. To electrode raising cylinder.
17. Oil control valve.
18. Armature.
19. Current coil.
20. Armature springs.
21. Stator.
22. Circular collar.

of the armature springs are connected to levers which rest on the top of the piston and increase spring tension as the piston rises. The armature has a limited rotary movement in the laminated stator. A magnetic circuit is formed by the armature and the stator.

The current and voltage coils are mounted on the back portion of the stator. With no current in the coils, the armature springs hold the control valve open and the piston is in the down position. A current signal applied to the regulator coil rotates the armature, thus closing the control valve and raising the piston. The control valve is partially closed and the piston hovers at the center of its stroke when the furnace is operating at the desired arc current.

The hydraulic distributor valve, attached to the piston by the stirrup, controls the raising and lowering of the electrodes. When the distributor valve is in the upper position, hydraulic fluid is forced into the electrode cylinder raising the electrode. In the center position the valve is closed and no hydraulic fluid flows, thus holding the electrode stationary. The distributor valve in the lower position allows hydraulic fluid from the electrode cylinder to discharge into the supply tank, thereby lowering the electrode.

Current Control Circuit

Current from the current transformer is partially tapped by resistor R_1, as shown in Figure 10. The remainder passes through the current coil of the regulator. With the regulator accurately adjusted a coil current of 1.2 amps centers the hydraulic distributor valve and holds the electrode stationary. Rheostat R_1 can be set for arc currents from 6,000 to 20,000 amps. If the coil current exceeds 1.2 amps, the distributor valve rises, thus raising the electrode and reducing arc current. Coil current below 1.2 amps lowers the electrode and increases arc current.

The voltage coil is energized only if the arc voltage drops to zero. When the electrode contacts the charge, the arc voltage is zero and the differential voltage relay DR is de-energized. The relay contacts close and energize the voltage coil which raises the electrode at maximum speed.

Scrap falling against the electrode reduces the arc voltage to zero, operating the relay and raising the electrode clear of the scrap. This reduces the possibility of electrode breakage during meltdown and minimizes the undesirable overload condition.

The differential voltage relay also operates during

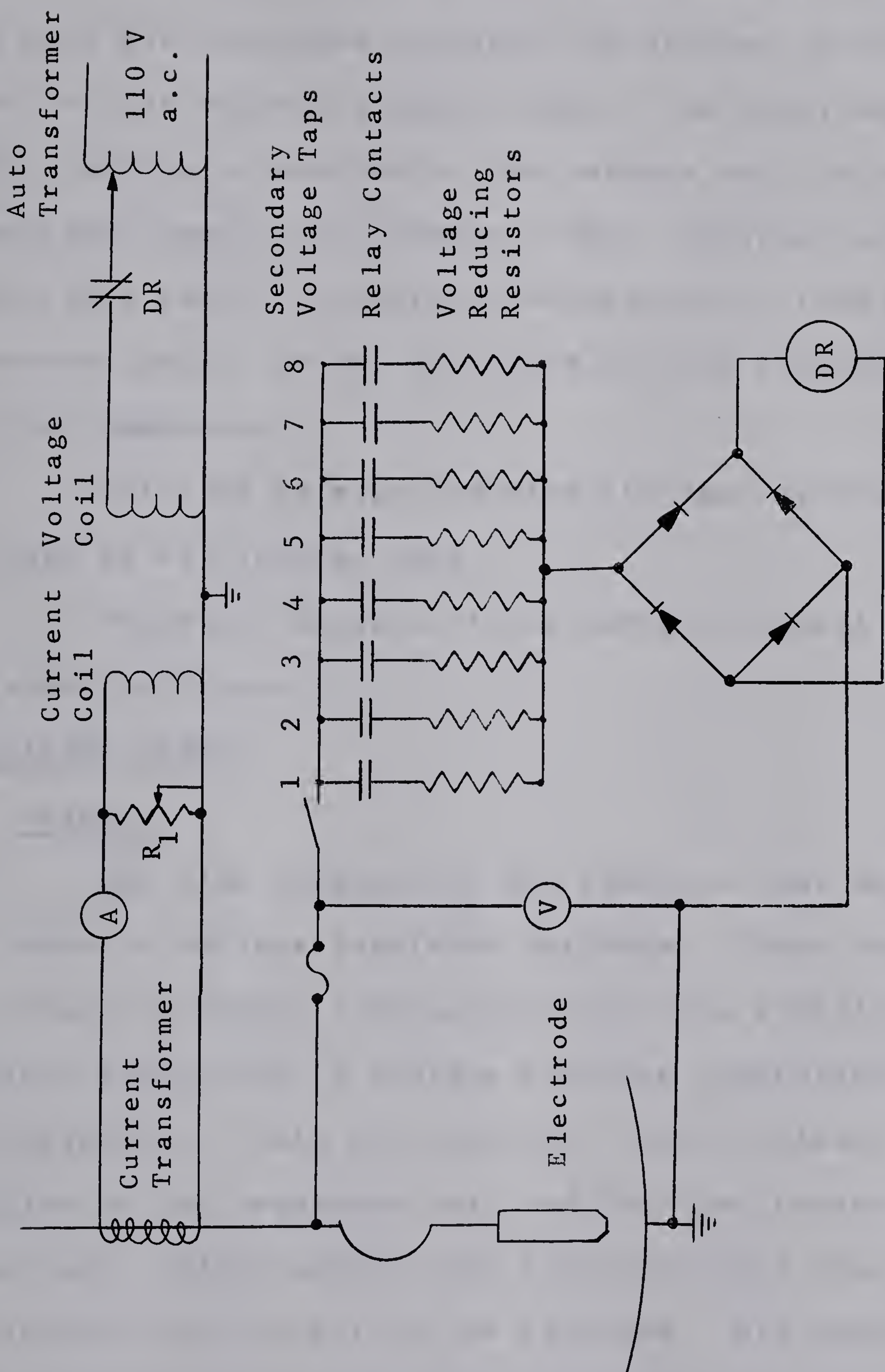


Figure 10 Current Control Circuit
(Single Phase)

furnace start up. As the three electrodes are lowered and only one electrode contacts the charge, no current can flow but the voltage drops to zero. The relay operates and a voltage is applied to the voltage coil raising the electrode clear of the charge. This continues until two electrodes reach the charge simultaneously, thus providing a current path. An arc is struck at each electrode and melting commences.

Relay DR is supplied with the same open-circuit voltage on all voltage taps.

The block diagram of the current control circuit is shown in Figure 11.

REGULATOR TESTS

Object

The time response of the regulator was determined by tests on various regulator sections. These tests were performed to secure information about the stability of the control system and to achieve a better understanding of the regulator. Both a.c. and d.c. control signals were applied to the regulator coil and the time response was measured. Adjustments to the regulator were also made to determine their affect on the response. All measurements were obtained while the furnace was shutdown for repairs.

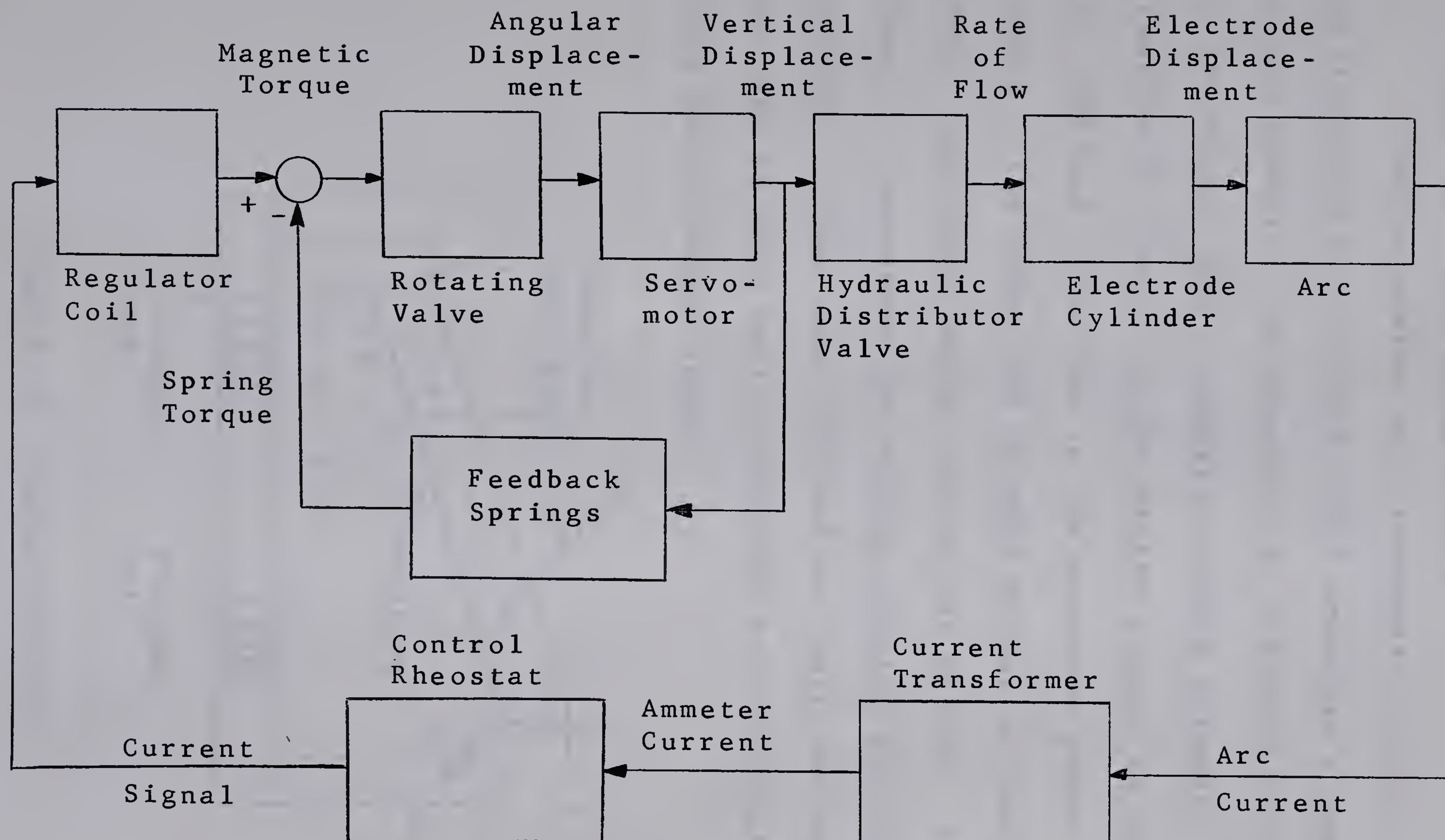
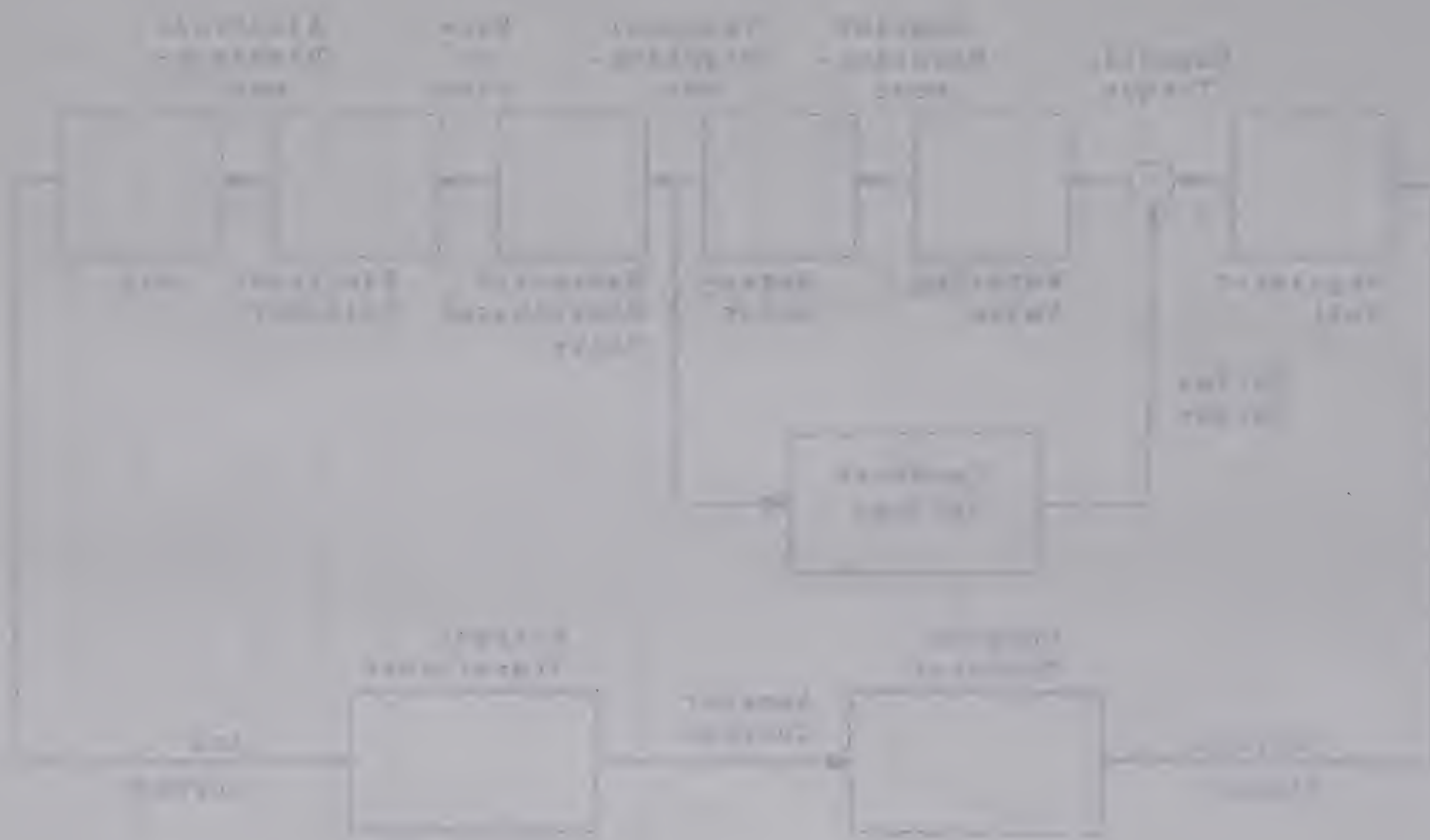


Figure 11 Block Diagram of Furnace Control Circuit (Current Control)



Regulator Coil and Armature

The regulator coil receives a control signal proportional to arc current which produces a magnetic field in the stator. The armature is situated between the poles of the stator and a magnetic torque attempts to pull the armature in line with the stator poles, as shown in Figure 12. Springs connected to the armature produce an opposing torque. The other end of each spring is connected to a lever that rests on the top of the piston. As the piston rises, it increases the spring tension and thus produces feedback. Stops are provided to limit the movement of the armature as only small rotations are required to open and close the rotating valve.

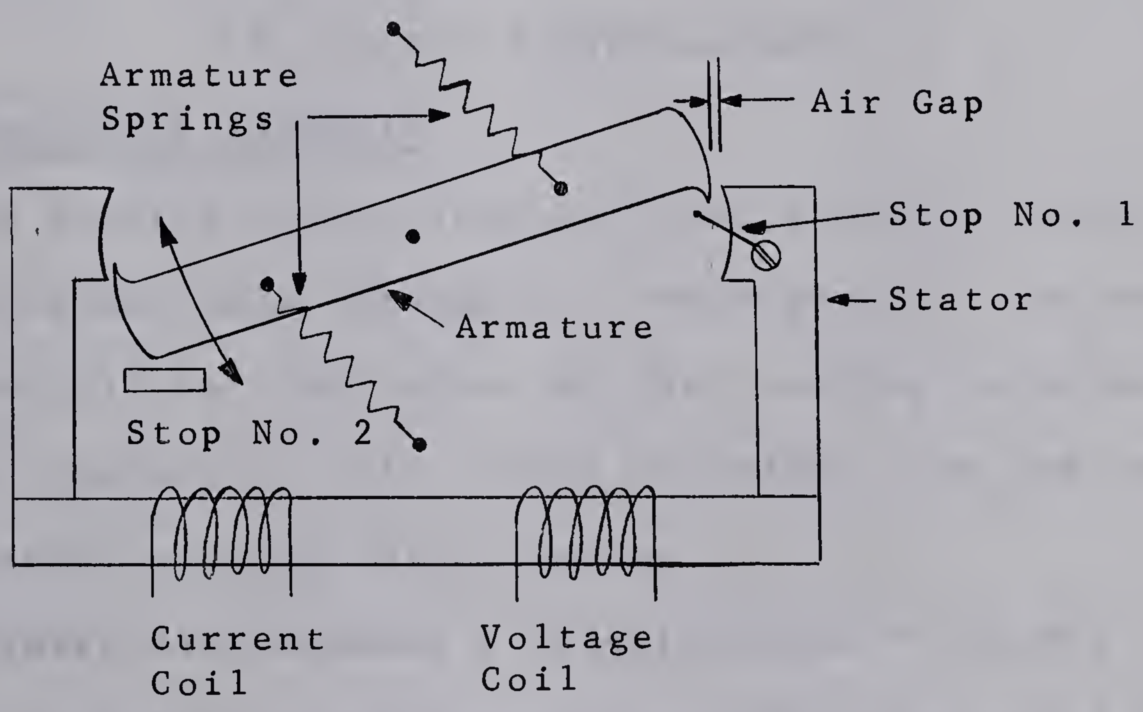


Figure 12 Stator Assembly

The transfer function of the coil is

$$G = \frac{K}{1 + Ts}$$

The time constant T is a result of coil inductance.

$$T = L/R$$

Voltage and current to the coil were measured to obtain impedance. Resistance of the coil was also measured.

$$V = 23 \text{ volts a.c.}$$

$$I = 1.2 \text{ amps a.c.}$$

$$R = 1.3 \text{ ohms d.c.}$$

$$Z = V/I = 19.2 \text{ ohms}$$

$$\omega L = \sqrt{Z^2 - R^2} = 19.1 \text{ ohms}$$

$$L = 0.0507 \text{ henrys}$$

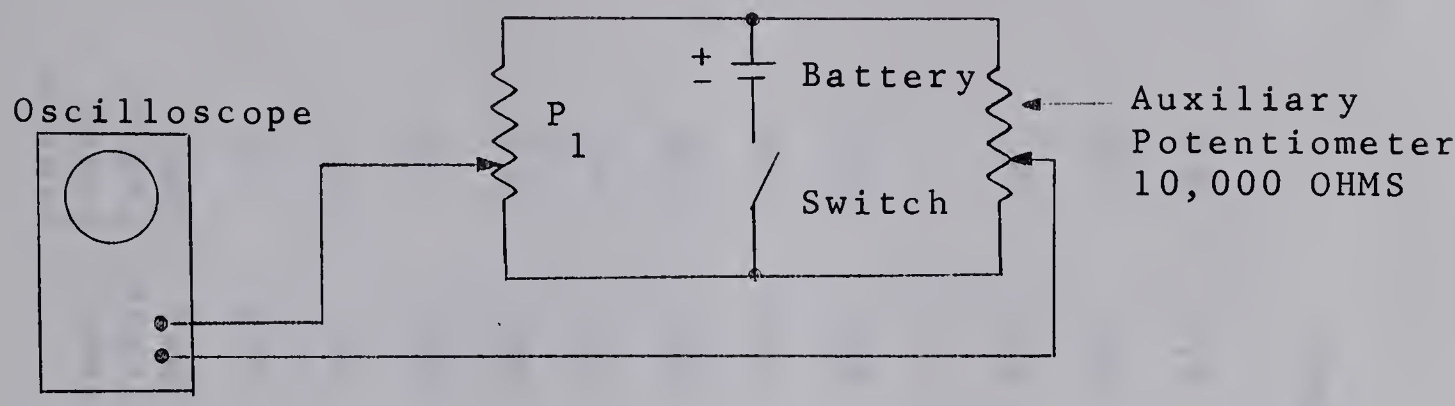
$$T = L/R = 0.0390 \text{ seconds}$$

Rotating Valve Assembly

The control valve, armature, and circular collar form the rotating valve assembly. See Figure 9. The stator assembly and all but the collar of the rotating valve assembly are immersed in oil. Vanes extending from the ends of the armature provide extra damping.

Angular displacement of the rotating valve was measured by mounting a single-turn potentiometer above the valve assembly and connecting its shaft to the collar.

Electrical connections were made as shown in Figure 13.



P_1 = 11,000 OHMS (Rotating Valve Test)

P_1 = 10,000 OHMS (Servomotor Test)

Figure 13 Potentiometer Test Circuit

A current signal was applied to the regulator coil and the response appeared as a trace on the scope. The current signal was selected to position the distributor at the midpoint. Adjustments were made to determine the effect of varying the air gaps and the length of the armature springs. Response to both a.c. and d.c. (full-wave rectified) current signals was measured. Table 2 shows the results of the tests performed on the rotating valve.

Examples of the scope traces are shown in Figures 14, 15, 16, and 17.

Test No.	Coil Current (AC amps)	Air Gap (in.)	Armature Spring Length (in.)	Rise Time to Peak Value (sec.)	Time to Reach Steady State (sec.)	Peak Value (mv)	Steady State Value (mv)
1	1.2	.014	1.65	.14	.57	160	45
2	1.2	.014	1.65	.12	.58	165	50
3	1.5	.014	2.16	.17	.62	142	96
4	1.5	.014	2.16	.12	.56	162	96
5	1.2	.011	2.16	.14	.60	175	95
6	1.2	.011	2.16	.14	.62	180	100
7	1.2	.016	1.61	.17	.47	200	90
8	1.2	.016	1.61	.16	.49	205	90
	(DC amps)						
9	.98	.016	1.61	.18	.60	225	85
10	1.16	.016	1.89	.17	.60	195	95
11	1.01	.016	1.61	.17	.54	255	85

TABLE 2 RESPONSE OF ROTATING VALVE ASSEMBLY

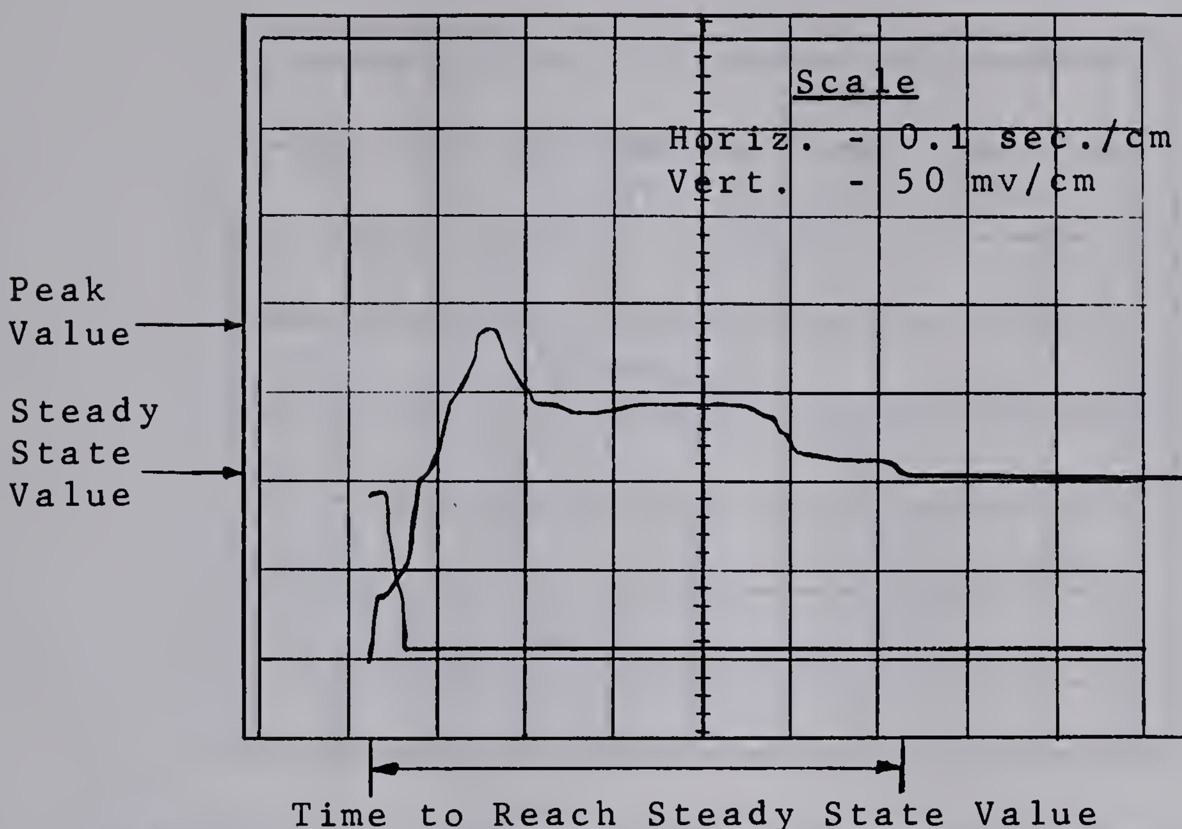


Figure 14 - Rotating Valve Response - Test 5

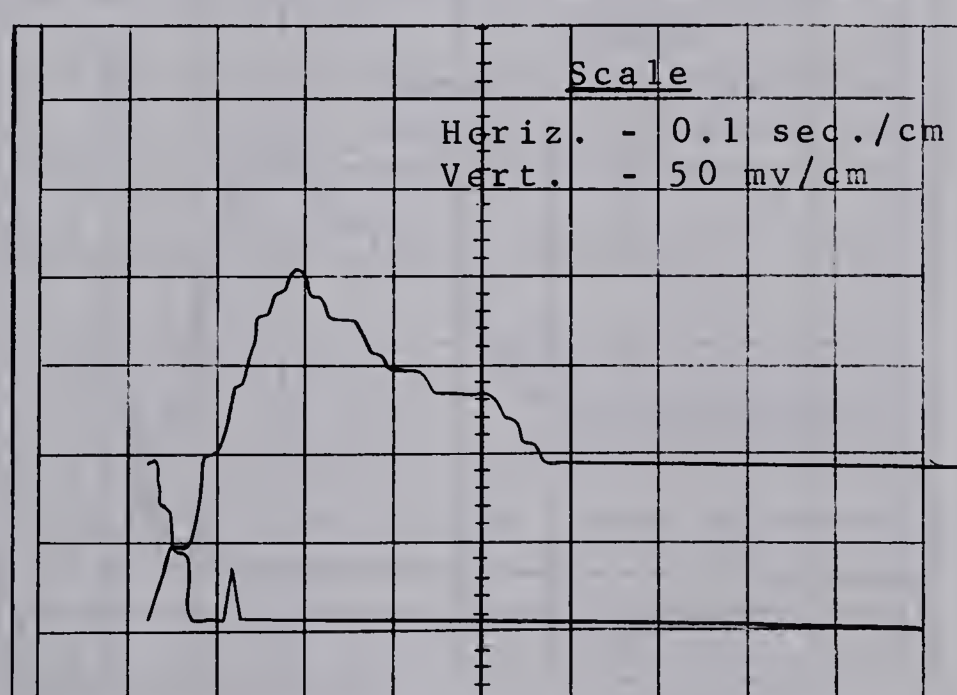


Figure 15 - Rotating Valve Response - Test 7

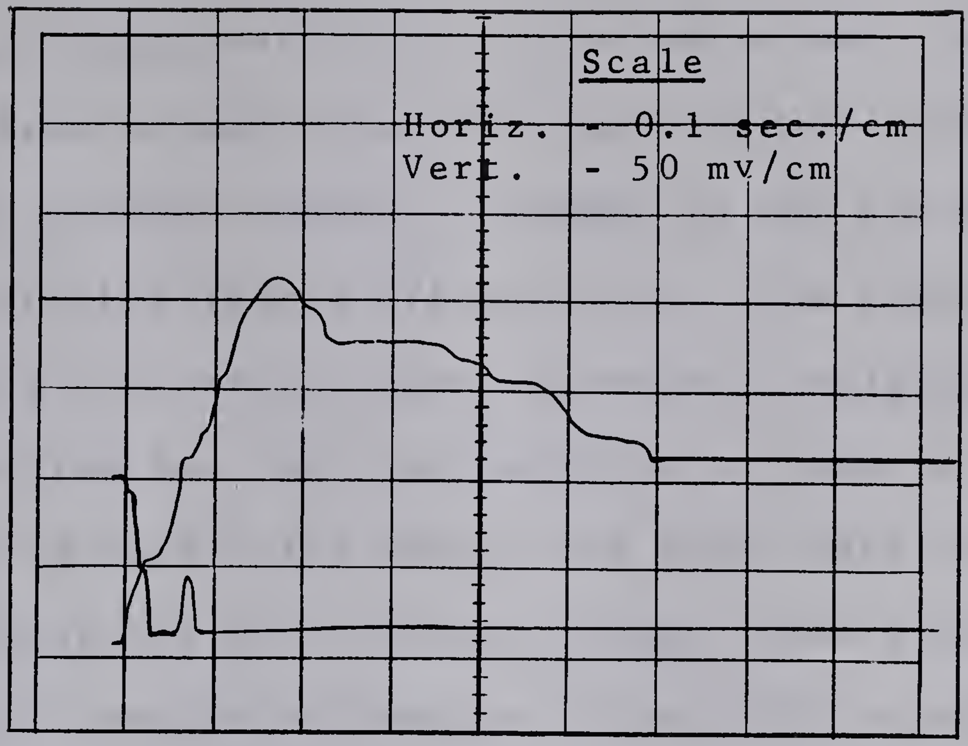


Figure 16 - Rotating Valve Response - Test 10

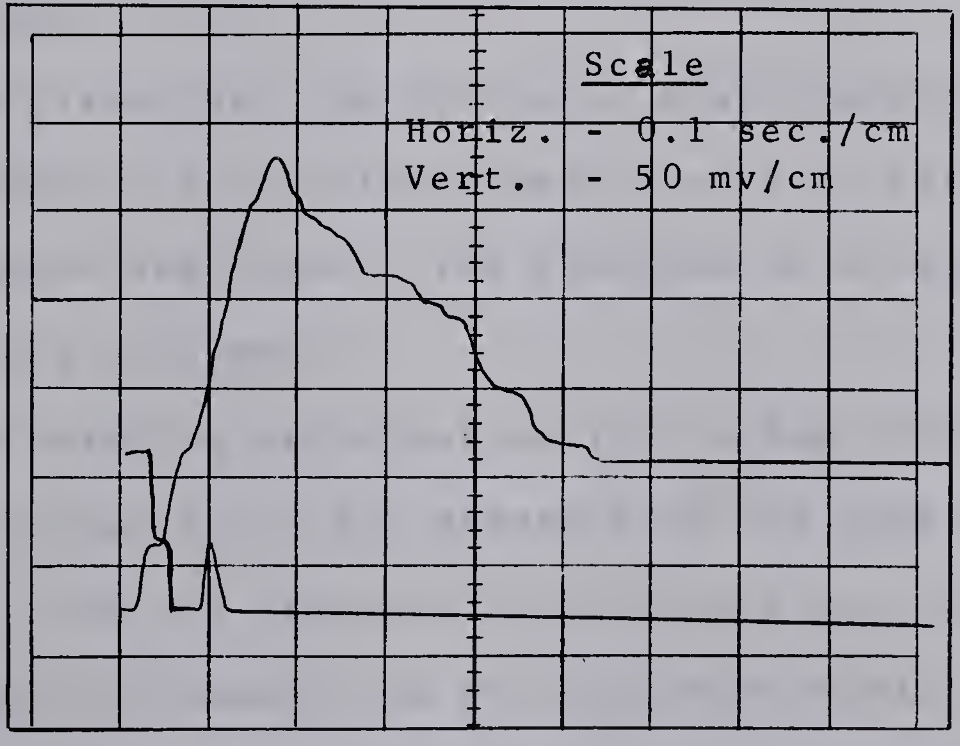


Figure 17 - Rotating Valve Response - Test 11

Only slight variations occurred in the time response and peak values obtained from the tests performed with an a.c. current signal. Changes to the air gap and spring tension had little affect on the time response.

The d.c. control signal produces a slightly longer time rise but the time required to reach a steady state value is nearly the same. The peak value obtained is higher using the d.c. control signal, indicating that the armature rotation is greater, thus fully closing the control valve.

The response of the rotating valve shows little change with changes in the air gap and the spring tension.

Servomotor

The piston and the hydraulic distributor valve act as a servomotor. A relatively small force is required to move the piston and control the position of a large mass (the electrode and mast).

The rotating valve seated in the top portion of the piston controls the oil pressure on the underside of the piston. The oil pressure raises the piston when the control valve is closed, and the hold-down spring beneath the regulator tank forces the piston down when the valve is open. The vertical position of the distributor valve controls the flow of hydraulic fluid to raise and lower the electrode.

The movement of the distributor valve is limited to 4 millimeters in each direction from the midpoint. The vertical displacement of the distributor valve was measured (using the circuit in Figure 13) by attaching a linear potentiometer to the stirrup connecting the piston and the distributor valve.

Response to a current signal applied to the coil was obtained, as before. Both a.c. and d.c. control signals were used. Air gaps and armature spring lengths were adjusted. The hold-down spring was also adjusted to determine its affect on the response. Table 3 shows the results of tests on the distributor valve where the final position of the distributor valve is the midpoint.

Examples of the distributor valve response are shown in Figures 18, 19, 20, and 21.

Except for test 5, time constants were determined for the curves obtained using an a.c. input signal. These curves approximate an exponential curve, where the time constant is defined as the time required to reach 63.2 percent of the final value.[7]

<u>Test 1.</u> The air gap and spring length settings were the same as those being used while the furnace was operating.

Test No.	Coil Current (AC amps)	Air Gap (in.)	Armature Spring Length (in.)	Time Constant (sec.)	Time to Reach Steady State (sec.)	Rise Time to Reach Midpoint (sec.)	Valve Lower-ing Time (sec.)	Steady State Value (mv)	Pos'n of Hold-Down Spring
1	1.2	.014	1.65	.210	.41		.33	520	down
2	1.5	.014	2.16	.285	.53		.37	540	down
3	1.2	.011	2.16	.205	.46		.31	500	down
4	1.2	.011	2.16	.270	.60		.25	530	up
5	1.2	.016	1.61		.66	.31	.25	530	up
6	1.2	.016	1.61	.195	.37		.27	500	up
7	1.2	.016	1.61	.210	.38		.25	550	up
	(DC amps)								
8	1.03	.016	1.61		.92	.33	.26	570	up
9	1.16	.016	1.89		.94	.34	.24	530	up
10	.91	.016	1.61		.62		.24	480	up
11	.91	.016	1.61		.66		.28	480	down

TABLE 3 RESPONSE OF THE DISTRIBUTOR VALVE

USING CENTERING CURRENT

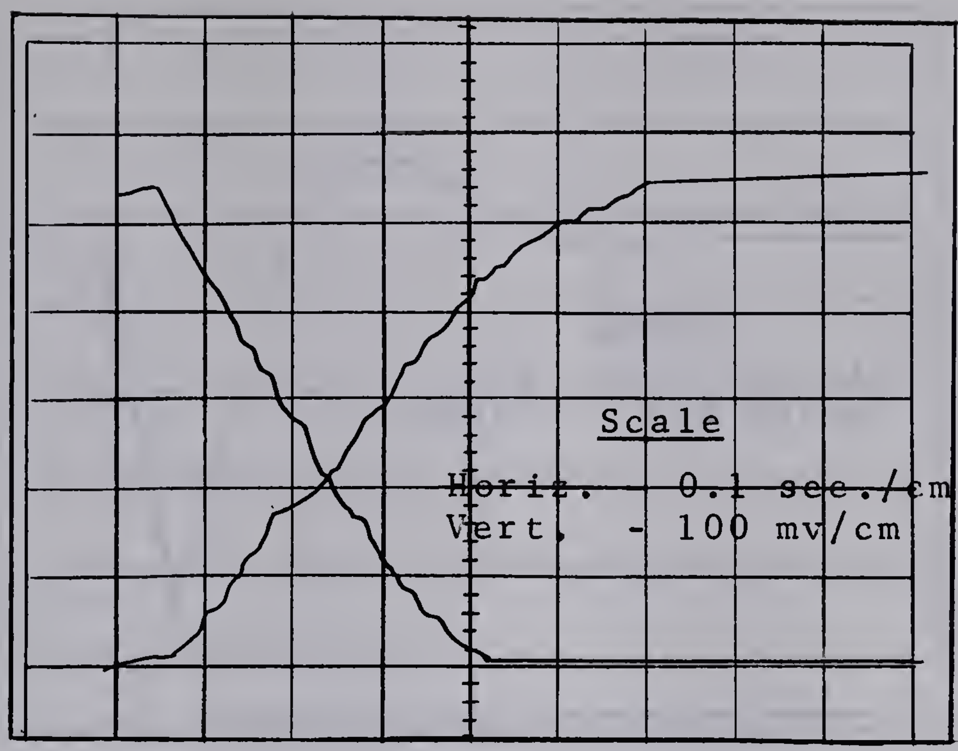


Figure 18 - Distributor Valve Response - Test 2

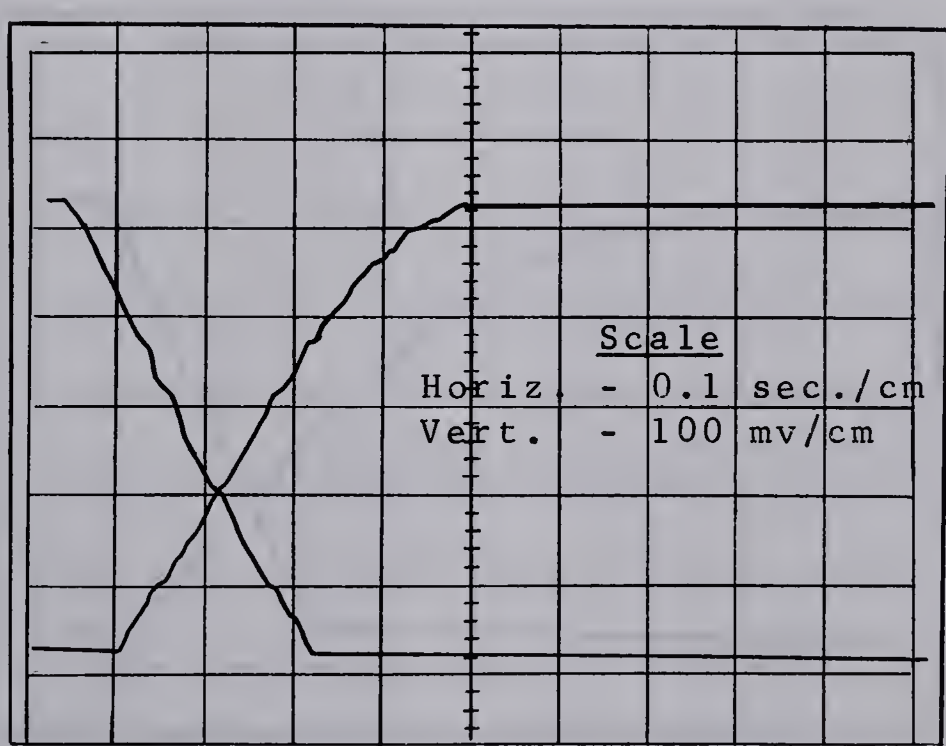


Figure 19 - Distributor Valve Response - Test 6

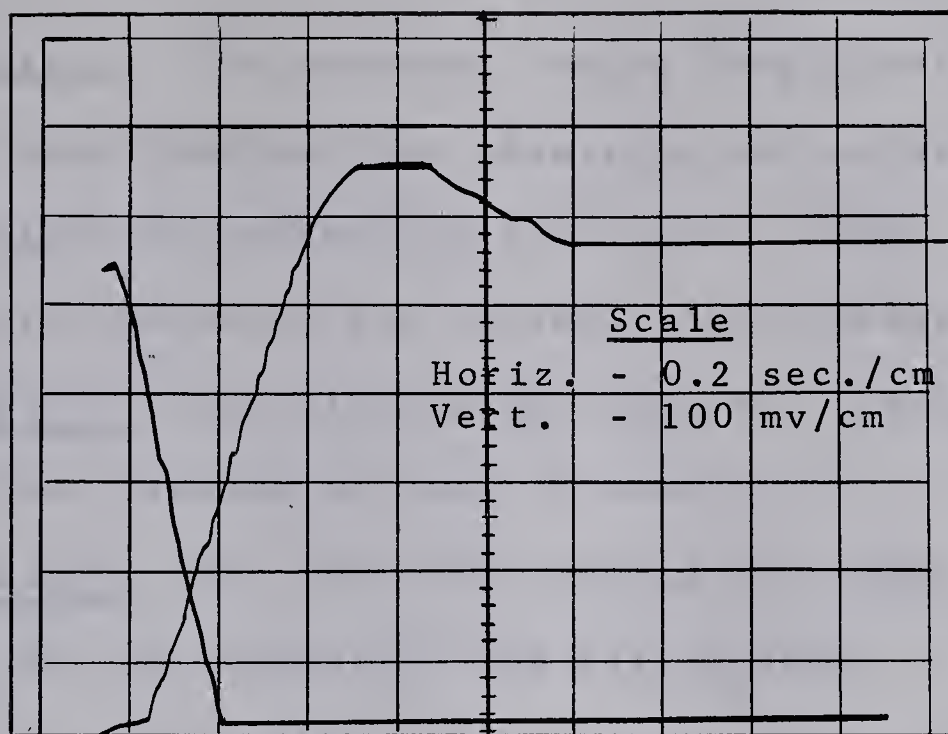


Figure 20 - Distributor Valve Response - Test 9

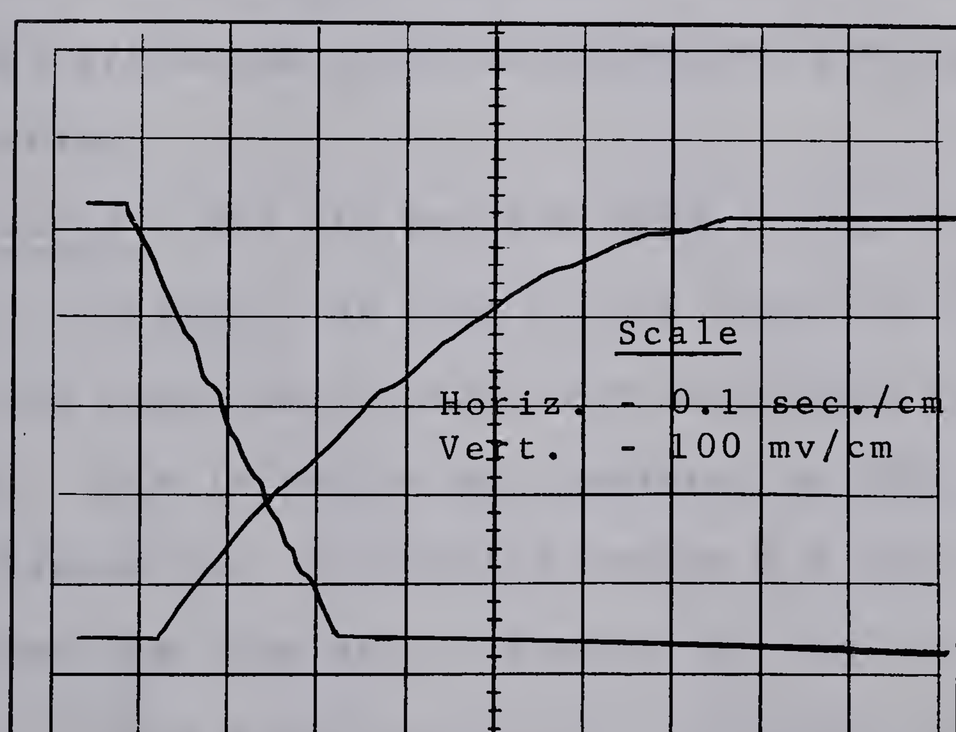


Figure 21 - Distributor Valve Response - Test 10

Test 2. The armature spring length was increased, producing more feedback and requiring an increase in the current signal to center the distributor valve. The time constant was increased due to additional feedback.

Test 3. The air gap was reduced, resulting in a time constant similar to that of test 1.

Test 4. The hold-down spring was compressed by two turns of the locknut on the piston shaft. This increased the distributor valve rising time and reduced the lowering time. An increase in the time constant was also evident.

The remainder of the tests using an a.c. current signal were performed with the hold-down spring in this upper position.

Test 5. The air gap and spring length were both adjusted. A faster rise time to the midpoint is indicated but the time required to reach a steady state value is increased. This is due to an overshoot of the midpoint, shown in Figure 22. A possible reason for this overshoot is that armature stop no. 1 (Figure 12) was displaced slightly allowing greater armature rotation; thus, the control valve closed completely and the distributor valve rose more rapidly.

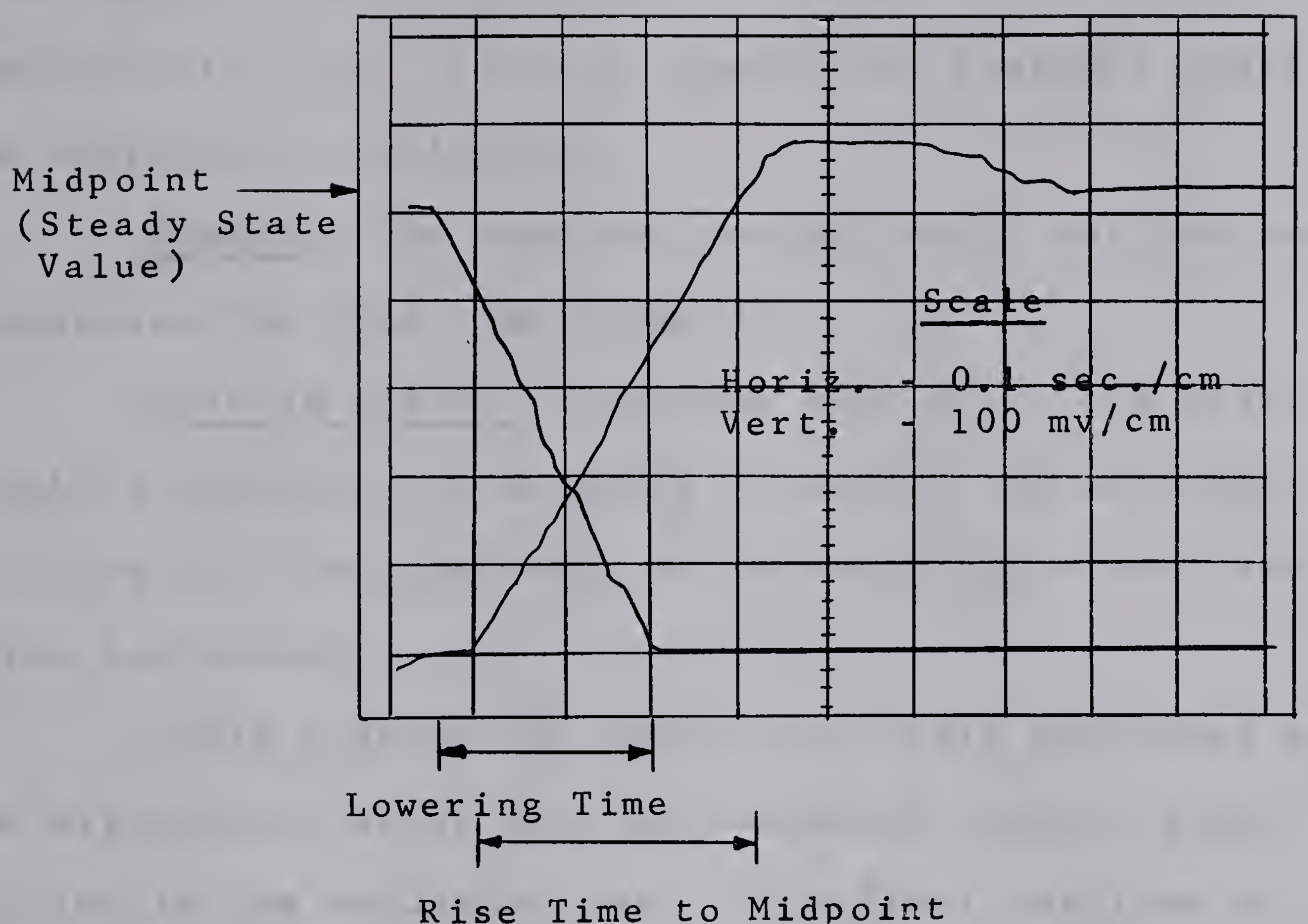


Figure 22 - Distributor Valve Response - Test 5

Test 6 and 7. The armature stop was returned to its former position while the other settings remained unchanged. No overshoot occurred and the fastest response times were obtained.

Test 8. The regulator settings were unchanged from test 7, but a d.c. control signal was used. The rise time to the midpoint was reduced but an overshoot condition

similar to that in test 5 was repeated. The tests on the rotating valve showed that the armature rotation was greater with a d.c. control signal; the probable cause of the overshoot in this case.

Test 9. The armature spring length was increased, increasing the rise time slightly.

Test 10 and 11. Armature stop no. 1 was displaced slightly reducing the armature rotation. No overshoot occurred but the time required to reach the steady state value increased.

Table 4 shows the results of tests performed on the distributor valve with an increased current signal applied to the regulator coil. The final position of the distributor valve was near its upper limit. All tests were performed with hold-down spring in the upper position.

Figures 23 and 24 are examples of the time response.

The response to the increased current signal was approximately a straight line. The d.c. control signal produced the fastest rise time.

Conclusions

Results of the tests carried out on the rotating valve and the servomotor indicated a slight difference in the response between a.c. and d.c. control signals. The d.c. control signal produced an increase in the armature

Test No.	Coil Current (amps)	Air Gap (in.)	Spring Length (in.)	Rise Time (sec.)	Lowering Time (sec.)	Steady State Value (mv)	Valve Raising Rate (V/sec.)
12	1.5 a.c.	.011	2.16	.56	.38	860	1.54
13	1.5 a.c.	.016	1.61	.51	.38	840	1.65
14	1.4 a.c.	.016	1.61	.54	.37	780	1.44
15	1.25 d.c.	.016	1.61	.48	.38	800	1.67

TABLE 4 RESPONSE OF THE DISTRIBUTOR VALVE

(Increased Current Signal)

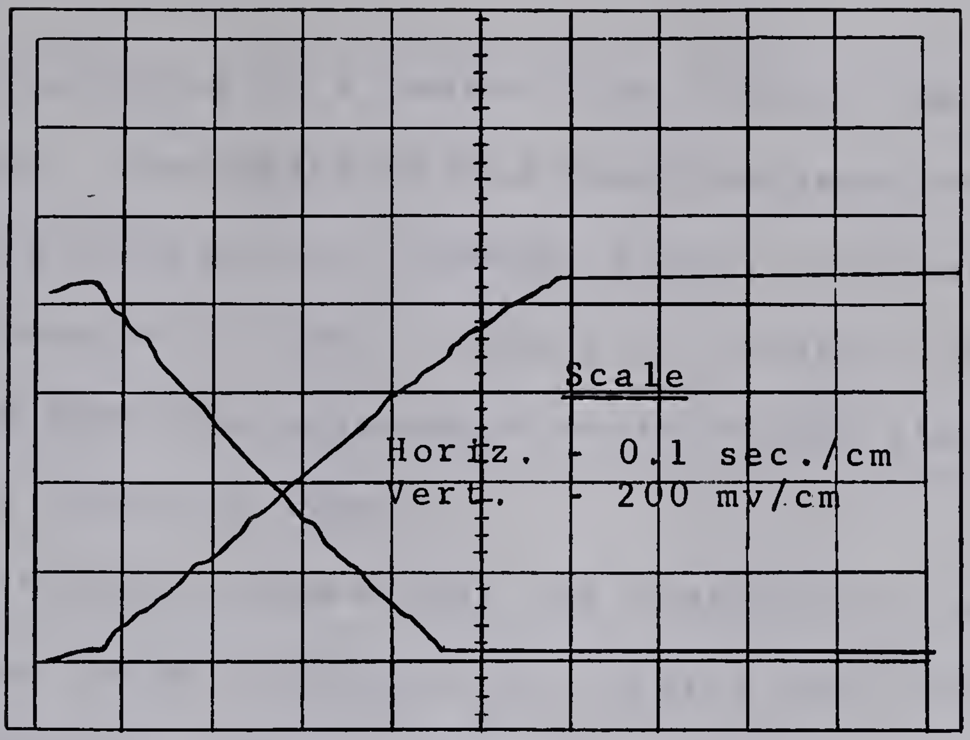


Figure 23 - Distributor Valve Response - Test 13

(with Increased Current Signal)

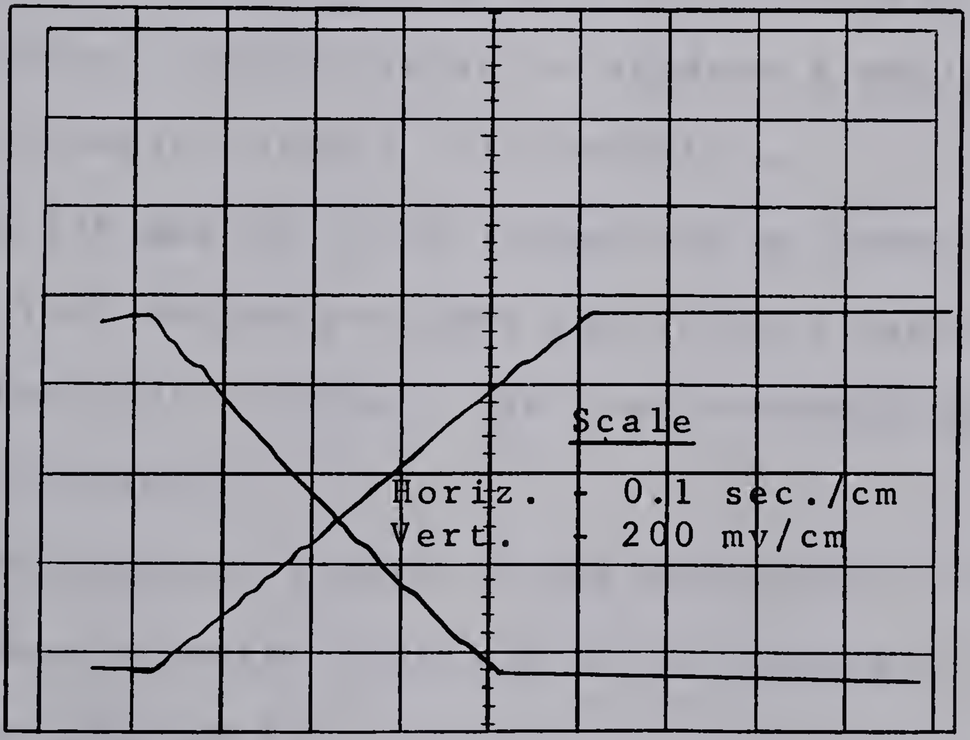


Figure 24 - Distributor Valve Response - Test 15

(with Increased Current Signal)

rotation resulting in a faster rise time of the distributor valve. The tests showed that the same result can be obtained with an a.c. control signal by adjusting armature stop no. 1 (as in test 5). However, it was not determined how this adjustment would affect the response to the d.c. control signal.

The tests showed that the distributor valve response time could be changed by varying the compression of the hold-down spring. Adjusting the oil flow is expected to have a similar result. According to the regulator specifications the raising and lowering speeds of the distributor valve should be equal. The raising time was longer than the lowering time in all of the tests. Opening the oil control valve to produce a small increase in oil flow would correct this condition.

An air gap of 0.016 inches and an armature spring length of 1.61 inches provided the fastest response times for the distributor valve. The time constant was approximately 0.2 seconds.

The response curves of the servomotor indicate that the open-loop transfer function of the regulator circuit can be approximated by

$$G = \frac{K}{S + 1/T}$$

where T = 0.2 seconds = time constant.

The hydraulic cylinder acts as an integrator producing an overall transfer function of

$$G = \frac{K}{S(S + 1/T)}$$

A control system with this type of transfer function is stable for all positive values of the gain constant K.

These tests were performed on only one phase. An interaction between phases may cause a condition of instability under certain conditions.

Adjustments to the regulator were made to improve the response time, but no significant changes in the overall efficiency were observed. Therefore, a new approach to the problem of improving the furnace performance was necessary. This is dealt with in the following chapter.

CHAPTER III

IMPEDANCE TYPE CONTROL

ADVANTAGE OF IMPEDANCE TYPE CONTROL

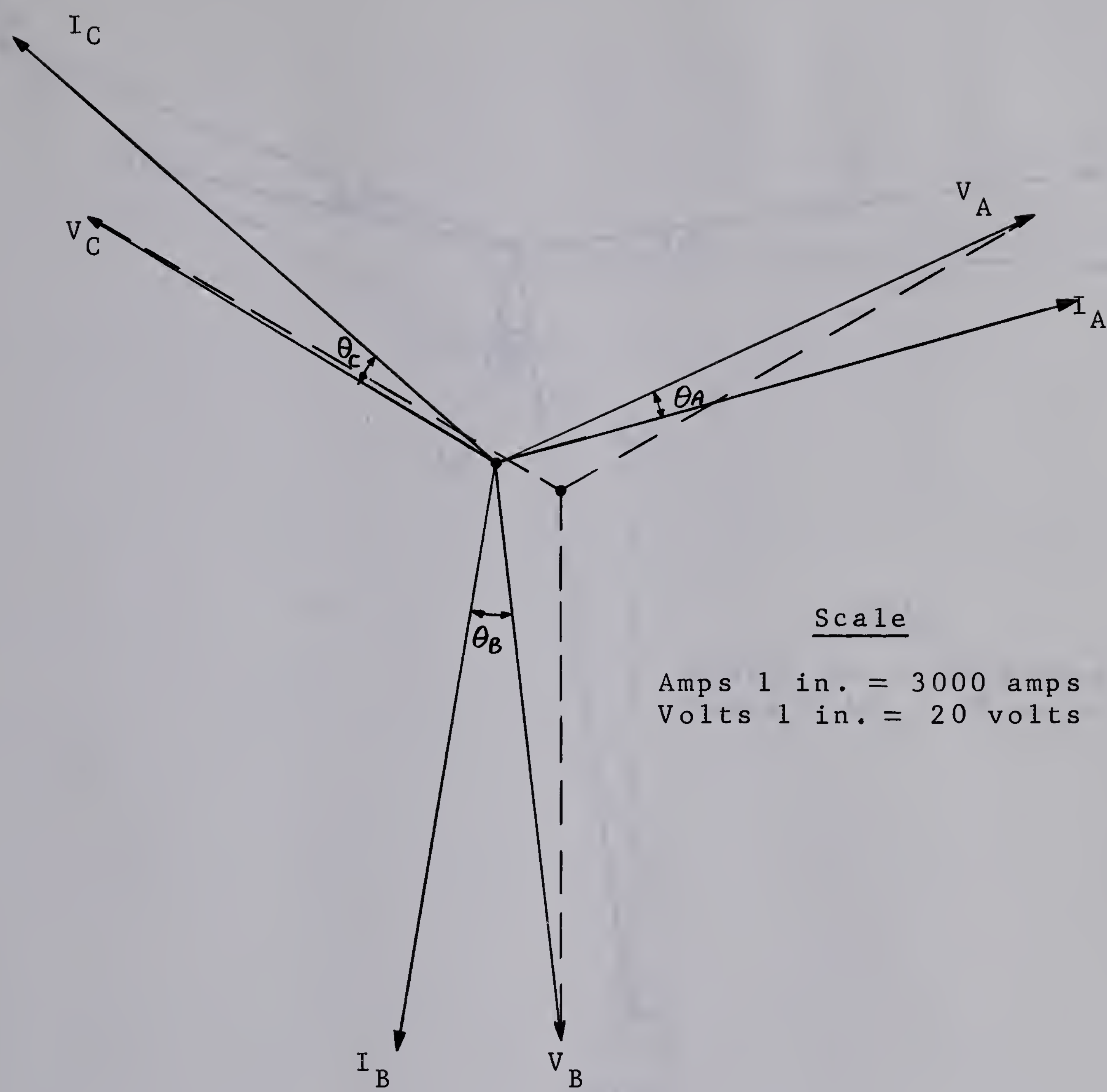
Literature on arc furnace controls indicates that impedance type control is considerably better than current control. An attempt is made to prove these assumptions.

Typical furnace operating conditions are shown in Figure 25. The phase-to-ground voltages are unbalanced while the currents are nearly equal. First it is assumed that the current and voltage in phase A remain constant. As this is quite possible, it greatly simplifies the following discussion.

Suppose that V_B increases and I_B decreases simultaneously due to a sudden change at phase B electrode. The phase C voltage is reduced resulting in a greater voltage unbalance, as shown in Figure 26. Since the transformer secondary is ungrounded, no ground current can flow and the sum of the phase currents must be zero.

$$\bar{I}_A + \bar{I}_B + \bar{I}_C = 0$$

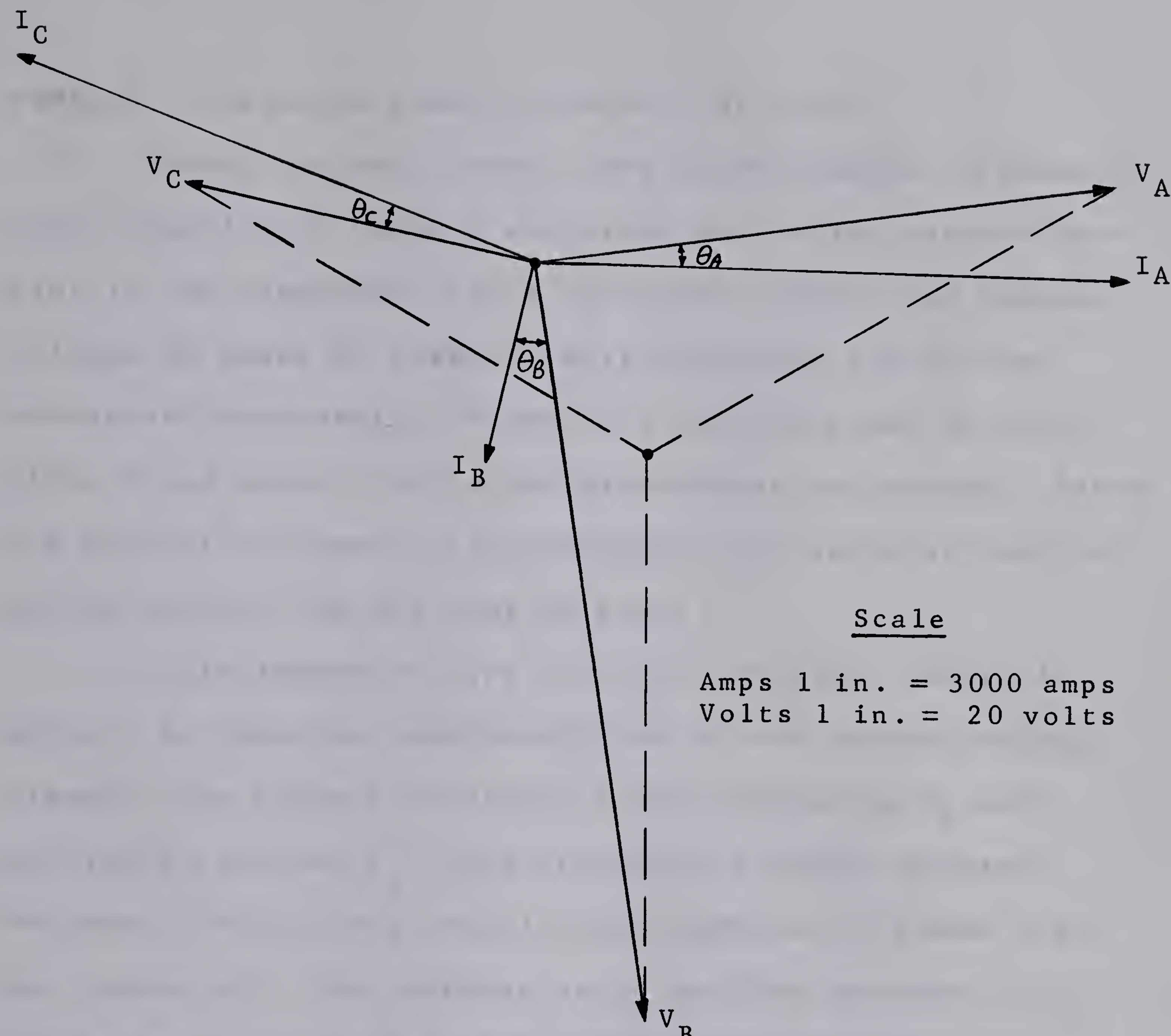
I_A remains constant, I_B and θ_B are known, therefore, I_C can be found. These current vectors are shown in Figure 26. I_C and θ_C remain nearly constant, but because of the



PHASE

	A	B	C
Volts	61.5	60	49.5
Amps	9400	9300	10000
KWatts	570	550	472
KVA	578	571	480
Power Factor	0.986	0.963	0.984
θ	9^{o}	15.8^{o}	10^{o}

Figure 25 Typical Voltage and Current Vector Diagram



	PHASE		
	A	B	C
Volts	61.5	81	38
Amps	9400	3200	9300
KWatts	570	240	344
KVA	578	259	354
Power Factor	0.986	0.925	0.985
θ	9^{o}	22.3^{o}	9.1^{o}

Figure 26 Voltage and Current Vector Diagram with a Disturbance at Phase B.

reduced voltage the power in phase C is less.

Using current control, the above changes in phase B cause lowering of phase B electrode due to the reduced current in the regulator. This increases current and reduces voltage in phase B, however, this condition may not be corrected immediately. There is a loss of power in both phase B and phase C until the disturbance is removed. Since the current in phase C is unchanged, its regulator does not act to correct for the loss of power.

With impedance type control, the power change in phase C is detected immediately due to the reduced voltage signal. The phase C electrode rises increasing V_C and partially reducing V_B, thus producing a better voltage balance. This occurs even if the condition at phase B is not corrected. The increase in V_C and the decrease in V_B forces an increase in I_B and increases the power in both phases.

A disturbance, such as that described above, may be caused by a piece of scrap falling away from phase B electrode into the melt; thus increasing the arc length and raising the arc voltage. Phase B electrode may be some distance above the melt and will require time for the original operating condition to be restored. Meanwhile phase C regulator keeps the voltages balanced. Therefore, the

impedance type control provides voltage regulation along with current regulation resulting in a steadier power output.

Conditions similar to the one described above occur frequently during furnace operations. The neutral point is kept nearer ground potential and the average power level is increased using impedance type control, resulting in better operating conditions.

<u>DESIGN OF IMPEDANCE TYPE CONTROL</u>

<u>Control Equation</u>

Current and voltage feedback are both present in impedance type control. The current and voltage signals must be converted to the same basic units and subtracted in an amplifier unit. These signals, along with a reference signal, produce a control signal which controls the regulator current. The regulation equation and error equation were given in Chapter I.

$$V_c = V_r + aK_1 I_a - \frac{bK_2 V}{V_t} \quad \text{(Regulation Equation)}$$

$$V_e = aK_1 I_a - \frac{bK_2 V}{V_t} \quad \text{(Error Equation)}$$

or

$$V_c = V_r + V_e$$

The reference signal alone must provide a coil current sufficient to center the distributor valve and hold the electrode stationary. This is the desired condition where current and voltage are constant and the error signal is zero. Then

$$V_c = V_r$$

and

$$aK_1 I_a - \frac{bK_2 V}{V_t} = 0$$

The block diagram for impedance type control is shown in Figure 27.

Amplifier Circuit

The amplifier chosen to provide the control signal consists of a "Silicontrol" unit (described in Appendix II) and a SCR (silicon controlled rectifier). The Silicontrol unit is a magnetic amplifier with four isolated d.c. control windings. The output is a square wave gate pulse which controls the conduction angle of the SCR. The current in the regulator coil is controlled by the SCR. The basic magnetic amplifier circuit is shown in Figure 28.

Rectified current and voltage signals are applied to the two low resistance control windings of the magnetic amplifier. These signals appear as voltages of opposite

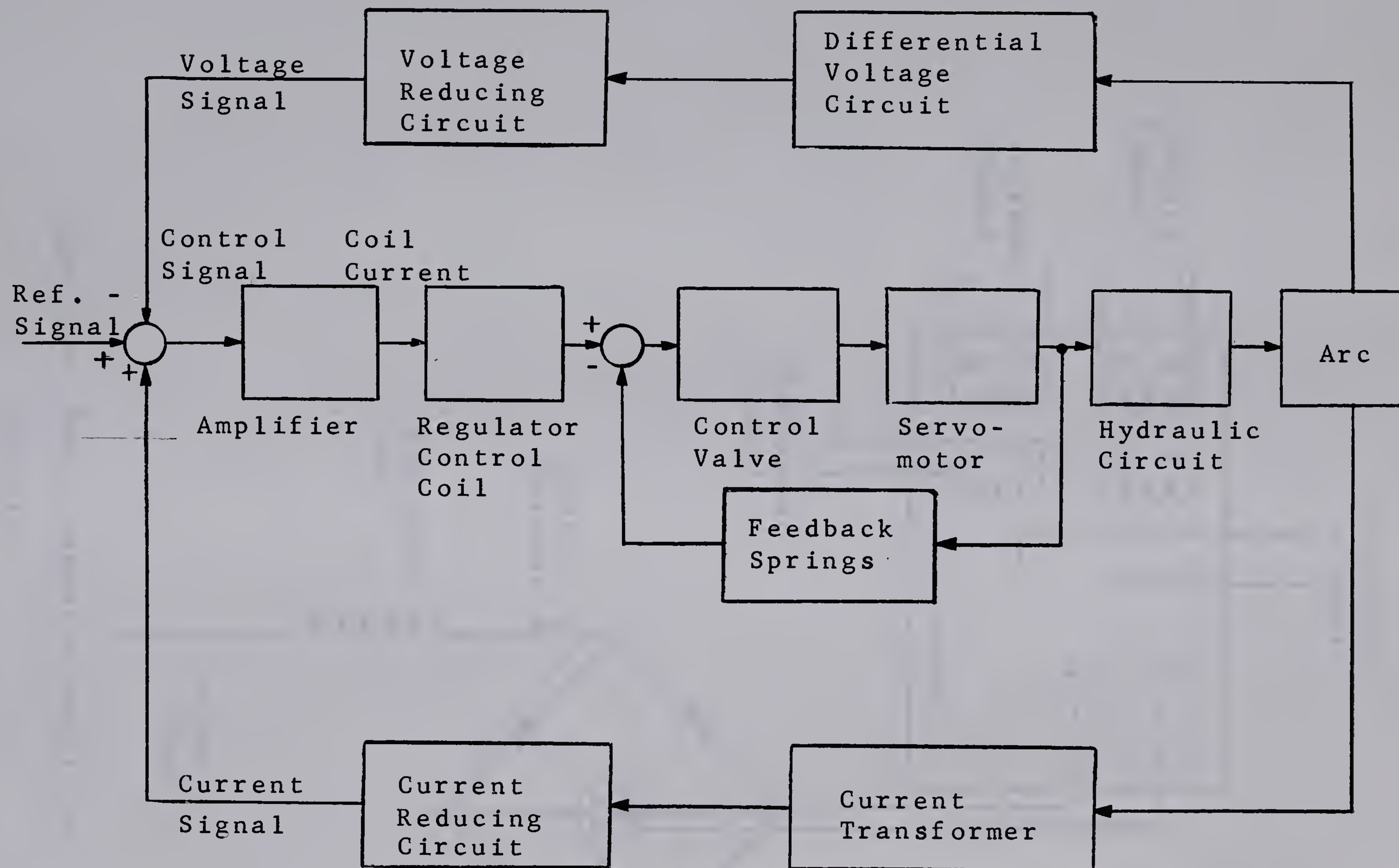


Figure 27 Block Diagram -

Impedance Type Control

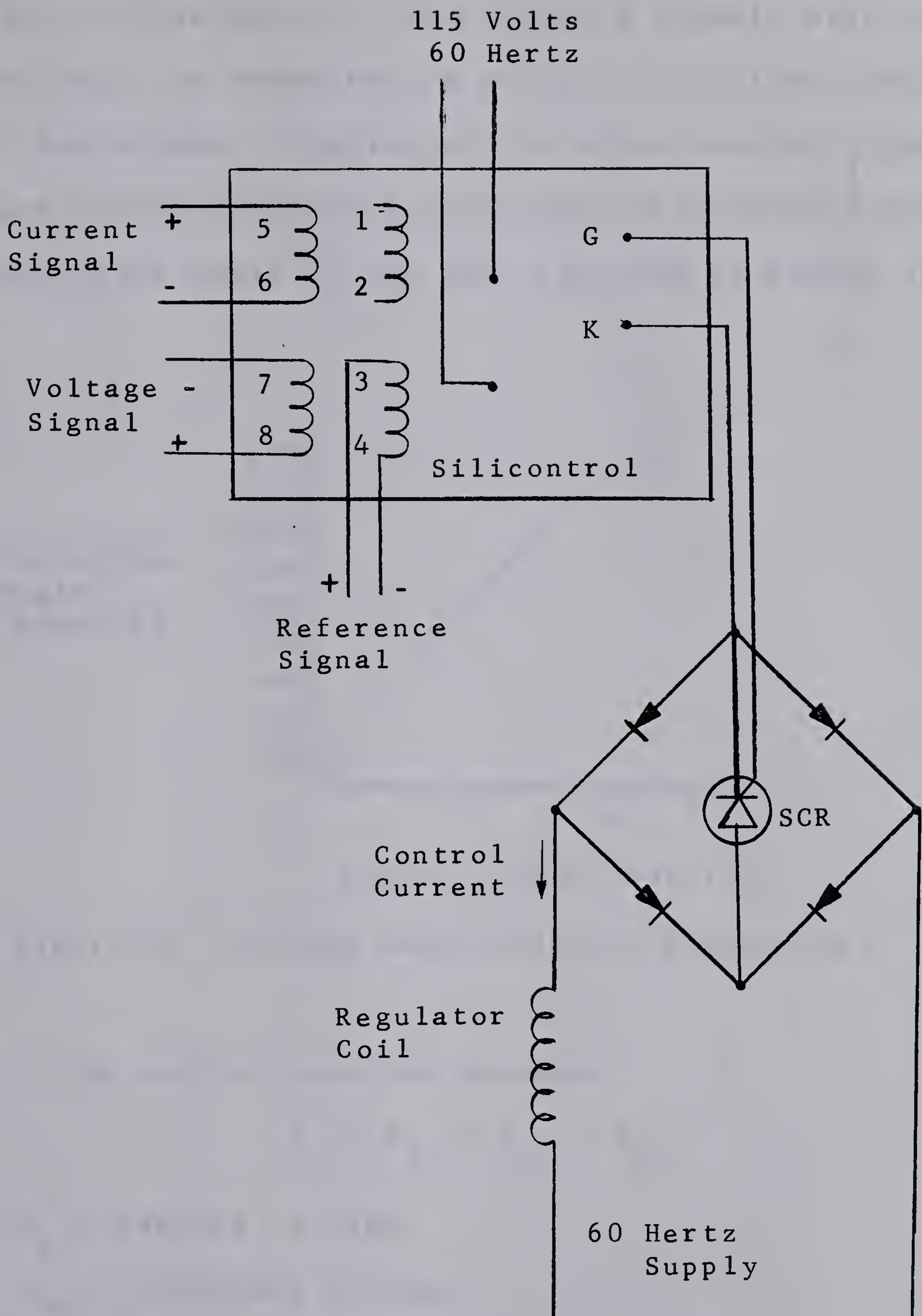
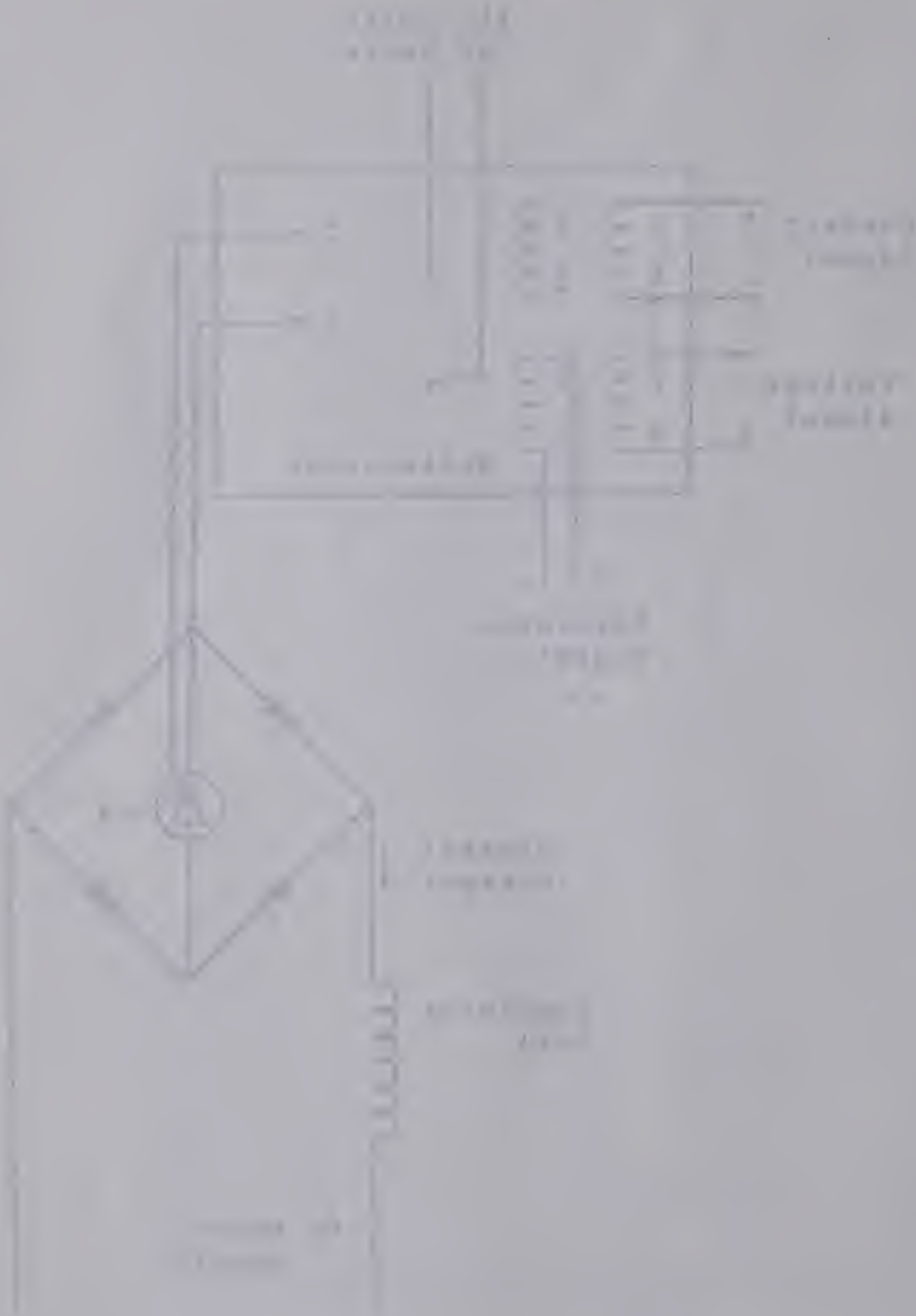


Figure 28 Basic Magnetic Amplifier

Circuit



polarity at this point. The reference signal, also a d.c. voltage, is connected to a third control winding of higher resistance. The sum of the three control signal voltages produces a square wave gate pulse which controls the conduction angle of the SCR, as shown in Figure 29.

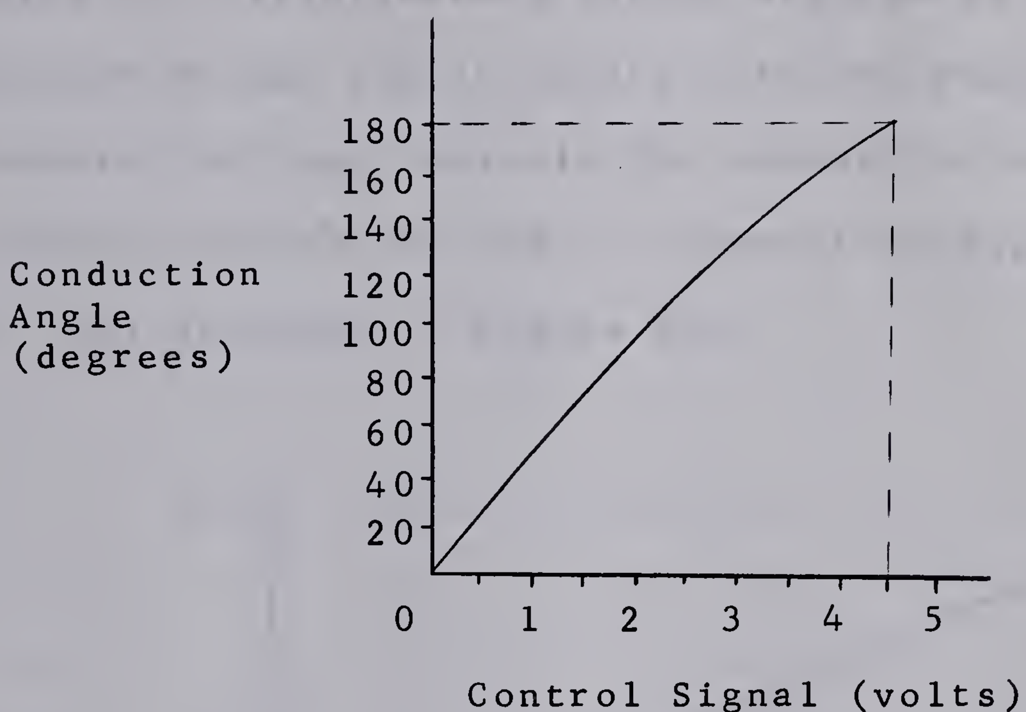


Figure 29 Voltage Sensitivity of Silicontrol

The control equation becomes

$$V_c = V_{34} + V_{56} - V_{87}$$

where V_c = control voltage

V_{34} = reference voltage

V_{56} = current signal

V_{87} = voltage signal

The error equation is

$$V_e = V_{56} - V_{87}$$

A bridge circuit allows the SCR to conduct over a full cycle. Alternating current passes through the regulator coil when the SCR is conducting. A 60 Hertz (1 Hertz = 1 cycle/second) supply voltage is connected across the bridge and in series with the regulator coil. The control voltage controls the conduction angle of the SCR which controls the flow of current through the regulator coil, as shown in Figure 30.

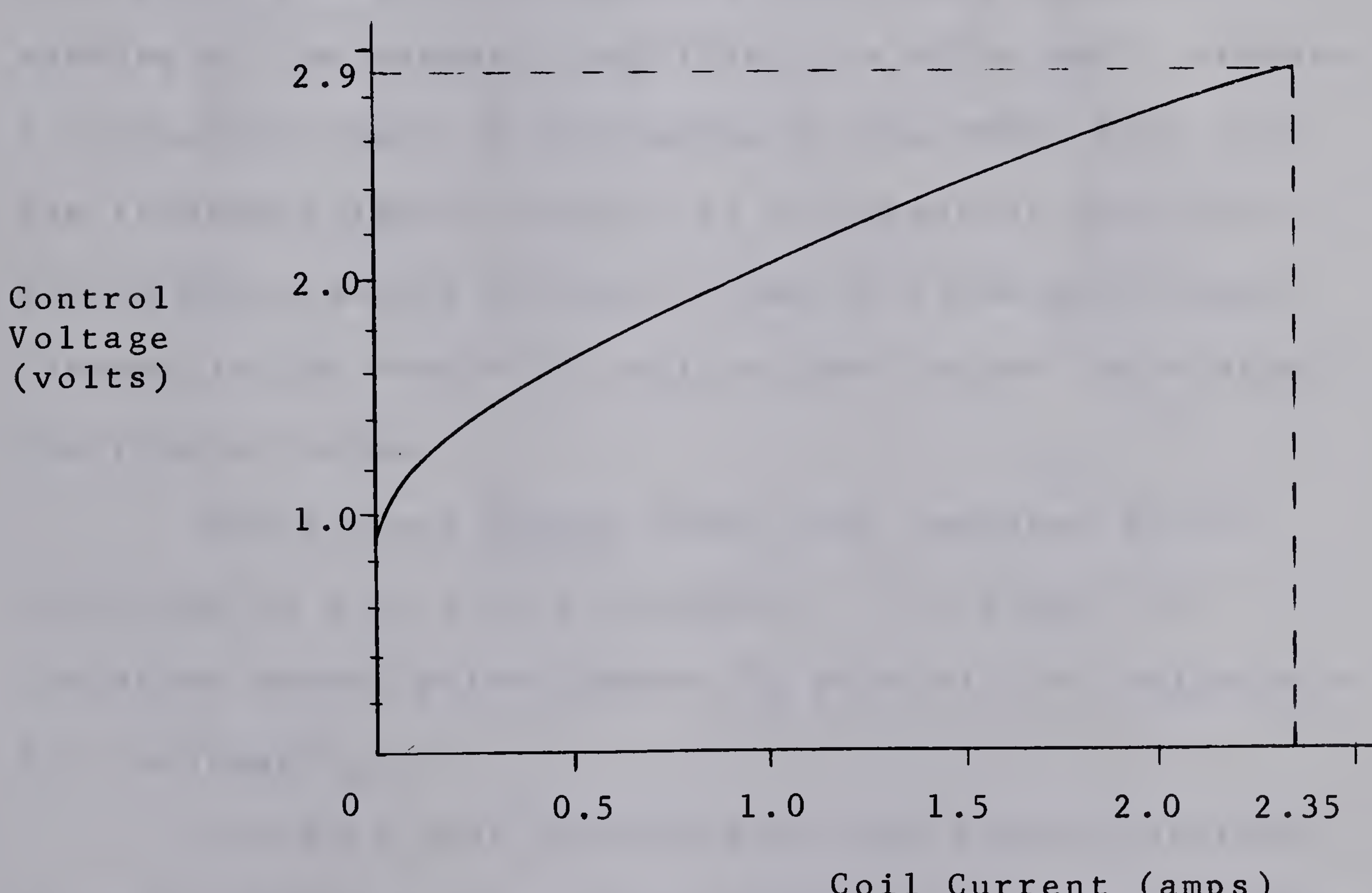


Figure 30 Control Voltage Versus Coil Current

A control voltage of 2.9 volts is sufficient to produce a conduction angle of 180 degrees since the gate signal is distorted by this circuit.

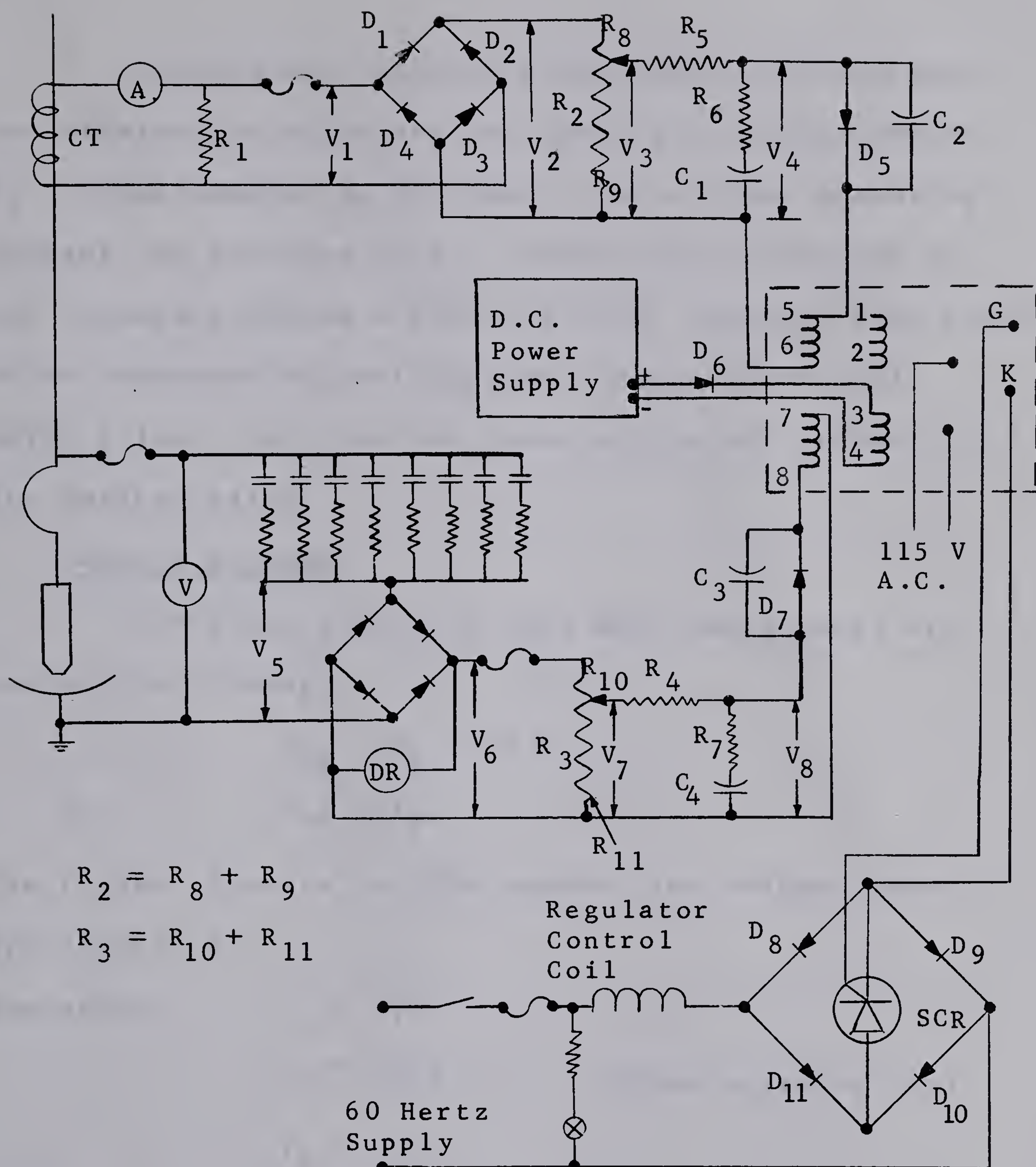
IMPEDANCE TYPE CONTROL CIRCUIT

The complete impedance type control circuit is shown in Figure 31. The current and voltage signals are rectified and filtered before being applied to separate control windings of the magnetic amplifier. The filter circuit is described in Appendix III.

The reference signal, supplied by a regulated d.c. power supply and connected to a third control winding of the magnetic amplifier, is adjusted to produce a conduction angle of 90 degrees in the SCR. With only the reference signal applied to the magnetic amplifier, the 60 Hertz supply voltage is set to allow sufficient current in the regulator coil to just center the hydraulic distributor valve.

The current signal taken from resistor R_1 is rectified by a full wave rectifier. The output is connected across potentiometer R_2 producing an adjustable d.c. voltage V_3.

The full wave rectified voltage signal obtained from the differential voltage circuit is connected across potentiometer R_3 producing an adjustable d.c. voltage V_7.



$R_2 = R_8 + R_9$

$R_3 = R_{10} + R_{11}$

R_1 = 3 ohms
R_2, R_3 = 5.0 K
R_4, R_5 = 1.0 K
R_6, R_7 = 1.5 K
C_1, C_4 = 1 uf

C_2, C_3 = 10 uf
D_1, D_2, D_3, D_4 – 1N1116
D_5, D_6, D_7 – 1N91
D_8, D_9, D_{10}, D_{11} – BYZ12
SCR – 2N177

Figure 31 Impedance Type Control Circuit

Desired arc currents from 6,000 to 20,000 amps are obtained by adjusting the setting of potentiometer R_2. Potentiometer R_3 is fixed. For a given operating current, an increase in arc current and a decrease in arc voltage produces a positive error signal. This results in an increased current through the regulator coil which raises the electrode reducing the arc current to the desired value.

Control Equation

The error signal is zero when the desired arc current is flowing.

$$V_{56} - V_{87} = 0$$

or $$V_{56} = V_{87}$$

The filter circuits for the current and voltage signals are identical.

Therefore, $$V_3 = V_7$$

$$V_3 = K_1 V_2 \qquad \text{(from Appendix III)}$$

$$V_7 = K_2 V_6$$

where $$K_1 = \frac{R_9 \times 10^3}{5 \times 10^6 + R_8 R_9}$$

and $$K_2 = \frac{R_{11} \times 10^3}{5 \times 10^6 + R_{10} R_{11}}$$

The current signal is obtained from resistor R_1.

$$V_1 = I_{CT}R_1$$

where $I_{CT} = \dfrac{I_a}{4000}$

This voltage signal is assumed to be a sine wave.

Then $V_1 = 0.707\ V_1max$ = rms value of a sine wave

and $V_2 = 0.637\ V_1max$ = average value of a full wave rectified sine wave.

$$\frac{V_1}{V_2} = \frac{0.707\ V_1max}{0.637\ V_1max} = 1.11 = \text{Form Factor}$$

Therefore, $V_3 = \dfrac{V_1}{1.11} K_1 = \dfrac{I_{CT}R_1K_1}{1.11}$

$$V_3 = \frac{I_aR_1K_1}{4000\ (1.11)}$$

$$V_4 = \frac{V_3}{3.16} \qquad \text{(from Appendix III)}$$

$$V_4 = \frac{I_aR_1K_1}{4000\ (1.11)(3.16)} = a\ K_1I_a$$

where $a = \dfrac{R_1}{4000\ (1.11)(3.16)}$

$$R_1 = 3 \text{ ohms}$$

$$a = 0.214 \times 10^{-3}$$

$$V_{56} = V_4 - 0.026 = a\ K_1I_a - 0.026$$

The voltage signal is obtained from the differential voltage circuit.

$$V_5 = 20 \frac{V}{V_t}$$

where V = operating secondary voltage (phase-to-ground)

V_t = secondary open-circuit voltage (phase-to-ground)

Figure 32 shows a curve of V/V_t versus I_a.

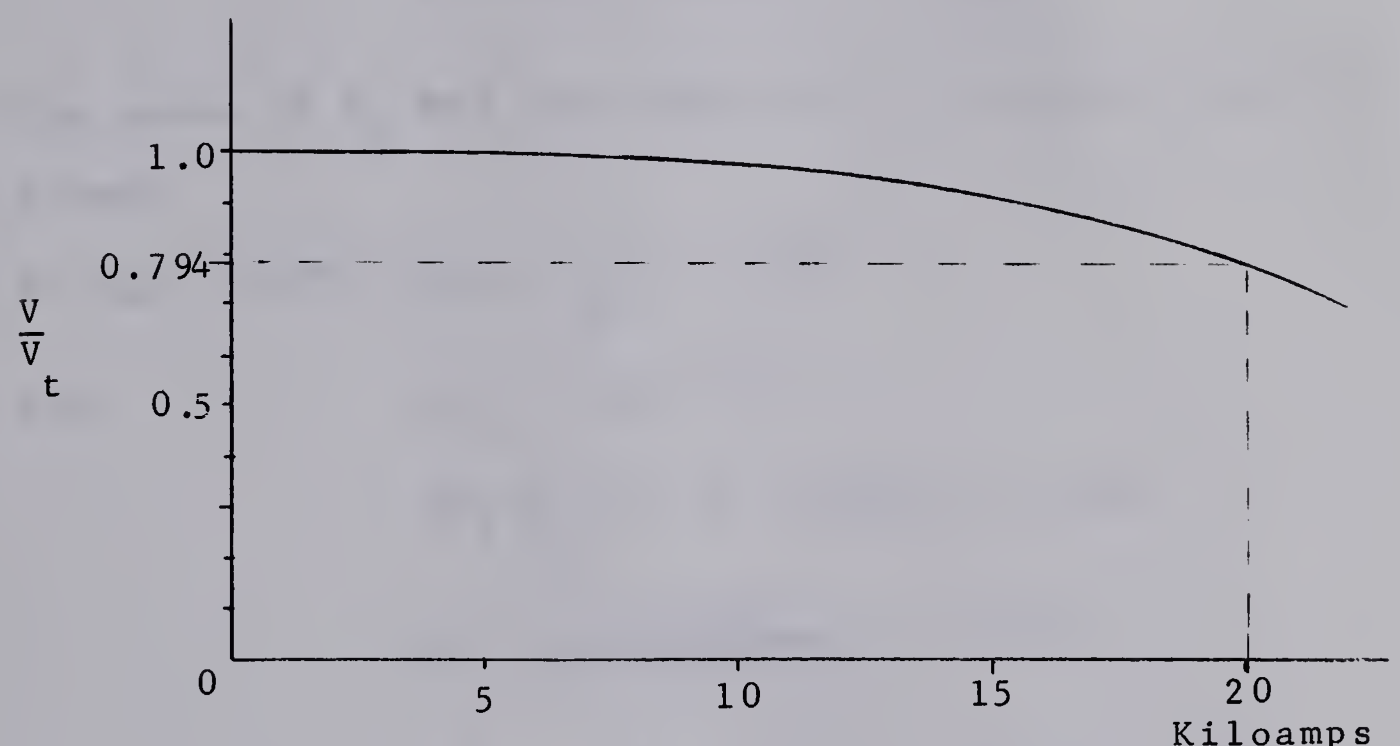


Figure 32 Arc Current Versus Voltage Ratio V/V_t

$$V_6 = \frac{V_5}{1.11}$$

and

$$V_7 = V_6 K_2 = \frac{V_5 K_2}{1.11} = 20 \frac{V}{V_t} \frac{K_2}{1.11}$$

$$V_8 = \frac{V_7}{3.16} = b K_2 \frac{V}{V_t}$$

where $$b = \frac{20}{1.11\ (3.16)} = 5.70$$

$$V_{87} = V_8 - 0.026 = bK_2 \frac{V}{V_t} - 0.026$$

The control equation is

$$V_c = V_r + V_{56} - V_{87}$$

$$V_c = V_r + (aK_1 I_a - 0.026) - (bK_2 \frac{V}{V_t} - 0.026)$$

$$V_c = V_r + aK_1 I_a - bK_2 \frac{V}{V_t}$$

The value of K_2 and the range of values for K_1 may be found.

At I_A = 20,000 amps, $\frac{V}{V_t} = 0.794$

and $$V_{87} = 1.0 \text{ volts}$$

$$bK_2 \frac{V}{V_t} = 1.0 + 0.026 = 1.026$$

$$K_2 = \frac{1.026}{(0.794)(5.70)} = 0.226$$

$$K_2 = \frac{R_{11} \times 10^3}{5 \times 10^6 + R_{10} R_{11}}$$

$$R_{10} = 5000 - R_{11}$$

$$K_2 = 0.226 = \frac{R_{11} \times 10^3}{5 \times 10^6 + 5000\ R_{11} - R_{11}^2}$$

$$5 \times 10^6 + 5000\ R_{11} - R_{11}^2 = \frac{R_{11} \times 10^3}{0.226} = 4410\ R_{11}$$

$$R_{11}^2 - 590\, R_{11} - 5 \times 10^6 = 0$$

$$R_{11} = \frac{590 \pm \sqrt{351{,}000 + 20{,}000{,}000}}{2}$$

$$= \frac{590 \pm 4510}{2}$$

$$R_{11} = 2550 \text{ ohms}$$

(The positive value must be used since negative resistance is meaningless here.)

The potentiometer R_3 is set at this value and remains fixed.

$$V_7 = (V_{87} + 0.026)\, 3.16 = 1.026\, (3.16)$$

$$V_7 = 3.24 \text{ volts}$$

$$V_3 = V_7$$

$$V_4 = aK_1I_a = 1.026$$

$$a = 0.214 \times 10^{-3}$$

$$I_a = 20{,}000 \text{ amps}$$

$$K_1 = \frac{1.026}{(20{,}000)(0.214 \times 10^{-3})} = 0.240$$

$$K_1 = \frac{R_9 \times 10^3}{5 \times 10^6 + 5000\, R_9 - R_9^2} = 0.240$$

$$R_9^2 - 5000\, R_9 + 5 \times 10^6 = \frac{R_9 \times 10^3}{0.240} = 4160\, R_9$$

$$R_9^2 - 840\, R_9 - 5 \times 10^6 = 0$$

$$R_9 = \frac{840 \pm \sqrt{(0.705 + 20) \times 10^6}}{2}$$

$$R_9 = \frac{840 \pm 4560}{2}$$

$$R_9 = 2700 \text{ ohms}$$

R_2 is set at 2700 ohms for I_a = 20,000 amps

At 6,000 amps arc current

$$\frac{V}{V_t} = 0.994$$

$$V_8 = bK_2 \frac{V}{V_t}$$

$$V_8 = 5.70\ (0.226)(0.994) = 1.282$$

$$V_{87} = 1.282 - 0.026 = 1.256 \text{ volts}$$

$$V_7 = 3.16\ V_8 = 4.05 \text{ volts}$$

$$V_7 = V_3$$

$$V_4 = aK_1 I_a$$

$$V_3 = 3.16\ V_4 = (3.16)(0.214 \times 10^{-3})(6000)K_1$$

$$V_3 = 4.05 = 4.05\ K_1$$

$$K_1 = 1$$

Therefore, $R_9 = 5000$ ohms

R_9 is set at 5000 ohms for an arc current of 6000 amps. The ratio K_1 varies from 1.0 at 6000 amps to 0.240 at 20,000 amps. These figures may not be exact since the calculations were based on a sine wave, but they do serve as a guide.

A comparison between current control and impedance type control is made in the following chapter.

CHAPTER IV

IMPEDANCE TYPE CONTROL VERSUS CURRENT CONTROL

INITIAL TESTS

Single Phase

Tests were conducted to compare the two types of control using impedance type control on one phase. A selector switch was provided to permit switching from current control to impedance type control while the furnace was operating. Comparison of the two types of control was made by checking consecutive sections of recordings.

The recorders used were Esterline-Angus, Model A601C, single pen recorders. Multipurpose meters were used to measure phase currents and phase-to-ground voltages. A recording a.c. wattmeter was used to measure single phase power.

Due to space limitations and for convenience only three recorders were used. The circuit parameters; volts, amps, and watts per phase were recorded simultaneously. A motor driven selector switch permitted the recording of the three phases in succession. All three parameters of each phase were recorded once per

minute or for longer periods if necessary.

Comparing the two types of control by this method indicated an improvement in regulation using impedance type control, as shown in Figure 33. However, the overall performance of the furnace showed little change.

It has been shown in Chapter III that impedance type control must be used on all three phases to prevent shifting of the neutral point and to provide effective power regulation. Figure 34 shows an example of a change in voltage and power in one phase with no change in the current. This occurred using current control. There was no indication of a similar condition occurring when impedance type control was used.

Identical control units were built for the other two phases so that complete impedance type control could be checked.

Three Phase

Three phase impedance type control showed a reduction in the power fluctuations compared to current control resulting in a higher average power input. Examples of the charts obtained are shown in Figures 35 and 36. These charts indicated that a

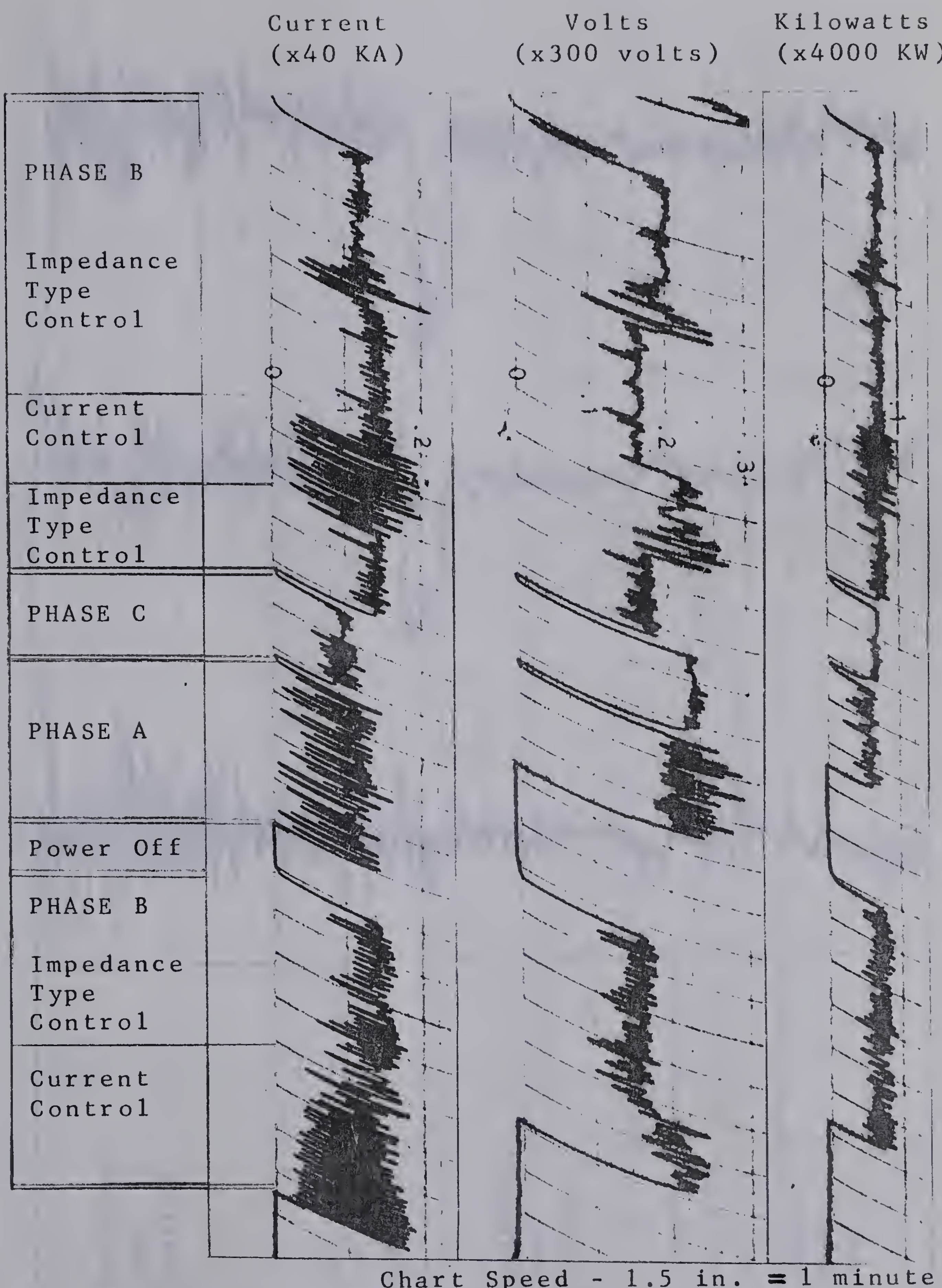


Figure 33 - Impedance Type Control Versus Current Control (1) (Single Phase)

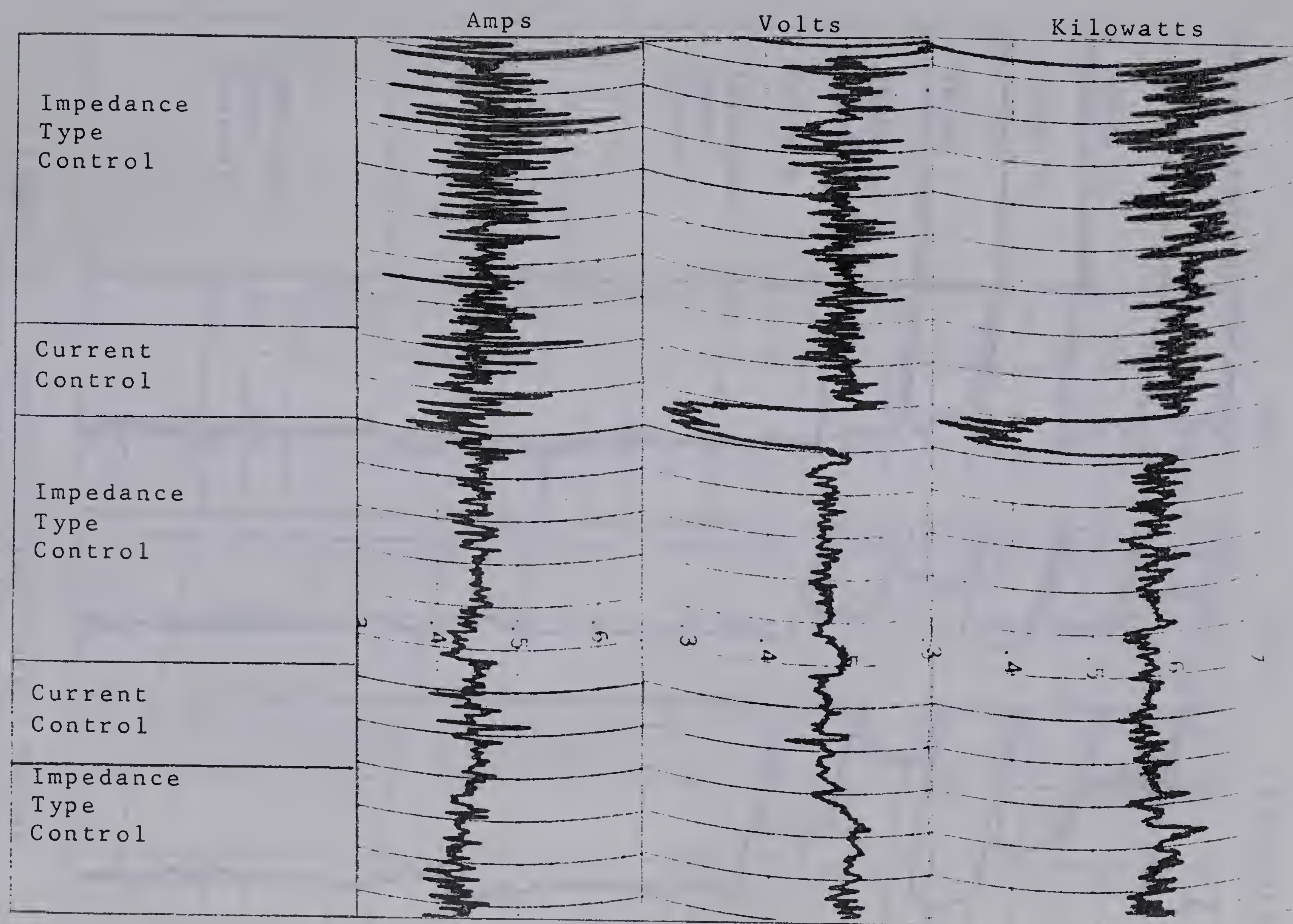
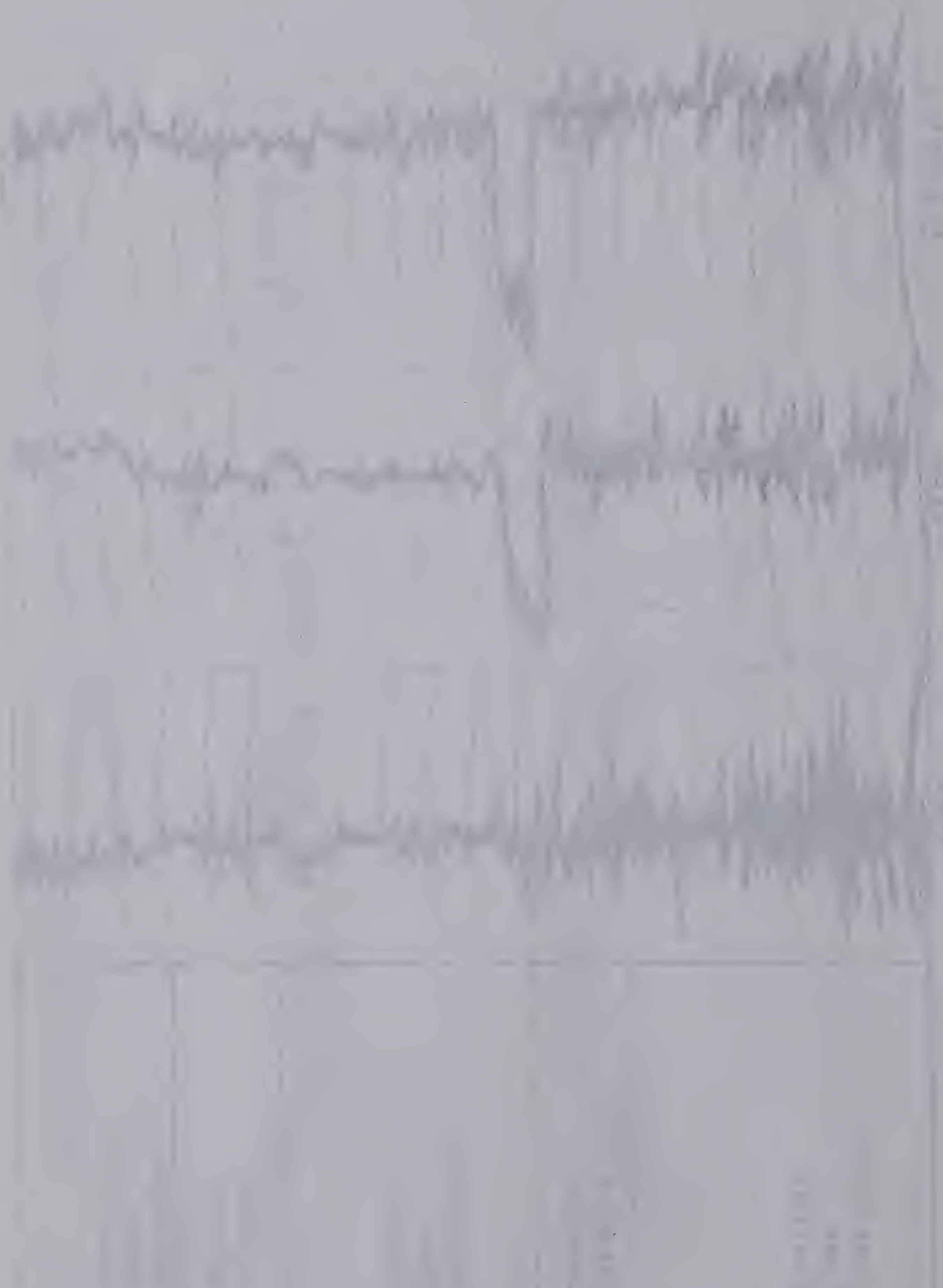


Figure 34 - Impedance Type Control Versus Current Control (2) (Single Phase)



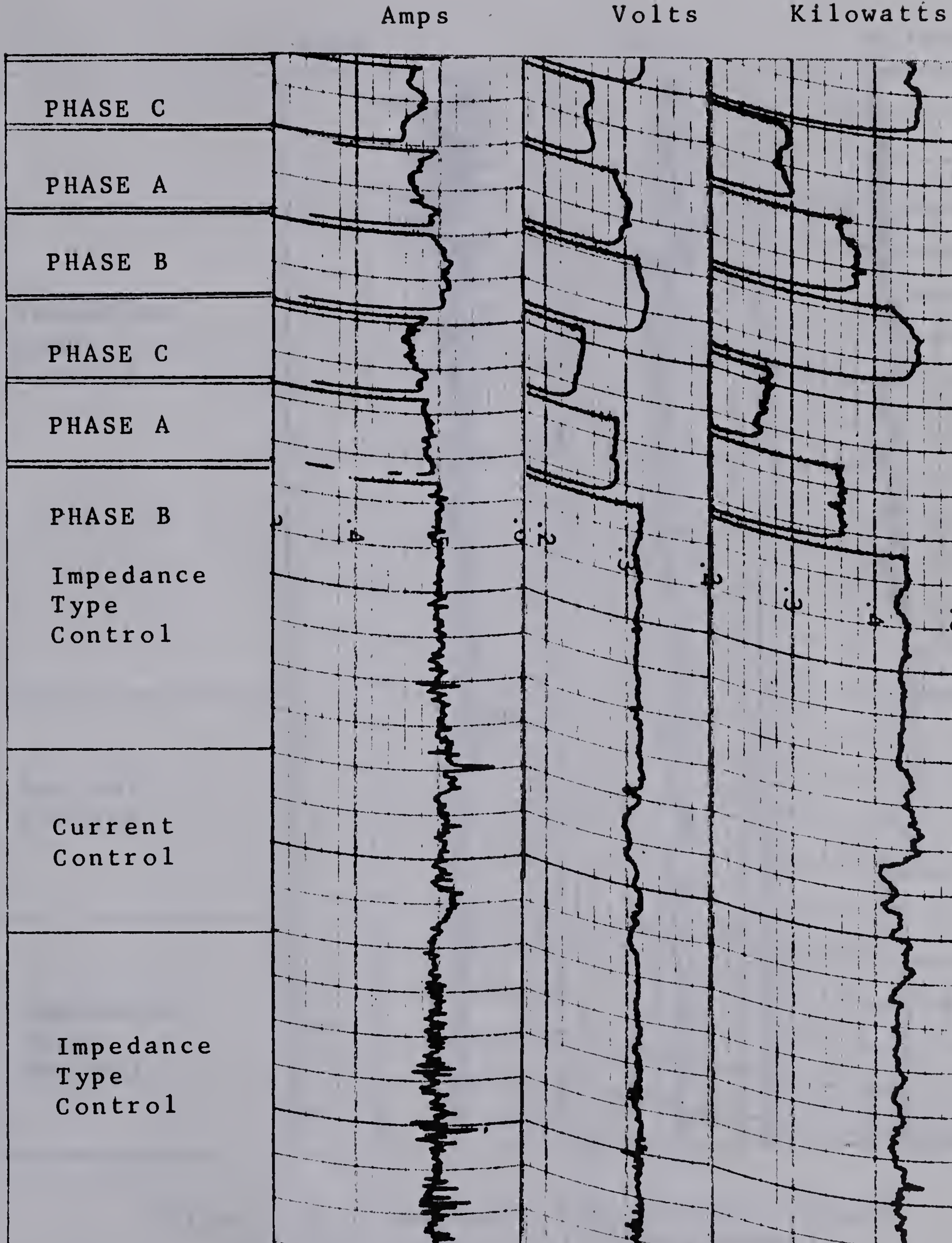


Figure 35 - Impedance Type Control Versus Current Control (3) (Three Phase)

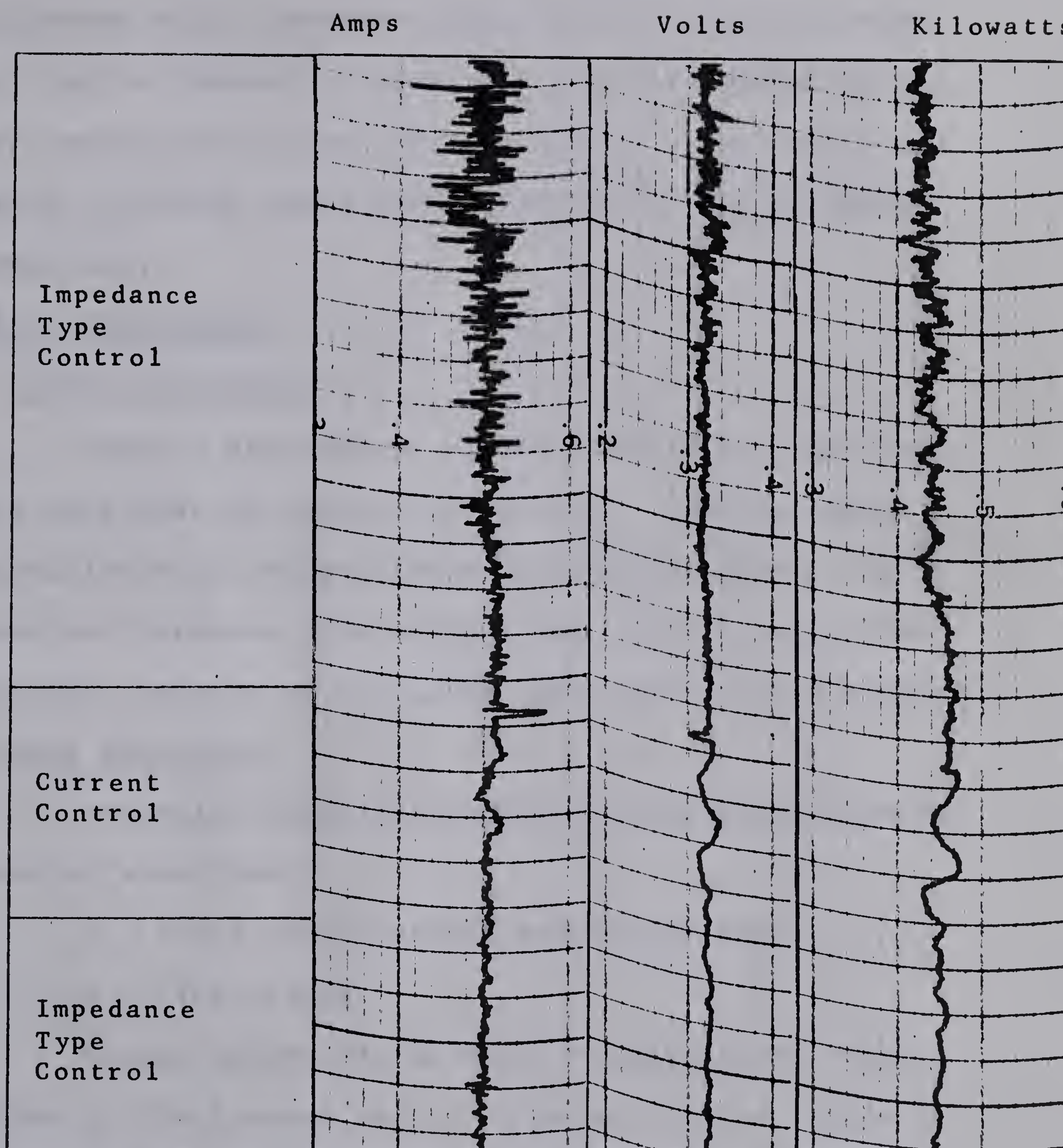


Figure 36 - Impedance Type Control Versus Current Control (4) (Three Phase)

reduction in the time required to produce a heat could be obtained using impedance type control. If the total heat time is reduced, a reduction in heat losses and power consumption is also expected due to more efficient heating. Further tests were necessary to verify these assumptions.

OVERALL PERFORMANCE

Control Variables

Overall performance of the furnace was examined using each type of control for a heat. Time and power consumption were the performance variables chosen for comparison purposes. An attempt was made to keep other variables constant or to reduce their effect to a minimum.

Main Variables

The main variables involved in the production of a heat of steel are:

1. Total charge weight and tap weight.
2. Time delays.

Charge weight is the total weight of the scrap charged in the furnace, while tap weight is the weight of steel tapped from the furnace at the end of a heat.

The total charge weight varies as much as ten percent between heats. The tap weight is proportional

to charge weight but direct measurement of the tap weight is not practical. The total weight of the steel cast is measured but due to uncontrollable circumstances this may vary considerably from the true tap weight. Power consumption was calculated in kilowatt-hours per ton charged. Changes in total charge weight are taken into account using this method.

Time delays are numerous and quite variable. Furnace charging requires a few minutes for each charge and the total number of charges varies. Electrodes must be slipped through the electrode holders as they burn off. This is usually done only once per heat, near the beginning of the first charge. New electrodes must be added periodically so that this time delay may vary between heats. Only a minute or two is required to slip electrodes while adding an electrode may take five or ten minutes. These are the normal time delays during meltdown.

Short time delays occur during the refining period when tap voltages are changed and when measuring temperature. Slagging operations vary with the grade of steel produced creating a variable time delay.

Other delays may occur due to breakdowns or

waiting which are unavoidable. The delays described above occur with the furnace power off. Power-on-time is used as a measure of performance and the time delays become insignificant. Heat losses increase as the time delays increase but except for abnormal delays this is negligible.

Time delays may also occur when the power is on. The furnace operator may have to wait for the lab to analyze a test after the required temperature of the melt is reached. The casting machine may not be available when the heat is ready to be tapped. The power is kept on to overcome heat losses and to maintain the temperature. The time lost per heat is fairly constant and the power consumed during this time is a small percentage of the total power. However, excessive waiting time must be taken into account.

<u>Minor Variables</u>

Variables of lesser importance are:

1. Grade of steel produced.
2. Ambient temperature.
3. Scrap quality.
4. Number of charges.

The affects of these can usually be reduced

by comparing consecutive heats using the two types of control.

The different grades of steel produced influence the refining time in varying degrees. Plain-carbon steels require a relatively short refining time while special steel grades require a longer and more extensive refining period. Power consumption, in general, is increased with specialty steels due to the increase in refining time.

The same grade of steel is usually produced for a number of consecutive heats depending on the demand. Therefore, a comparison made using current control on one heat and impedance type control on the next should be quite consistent.

The ambient temperature may affect the heat losses but a considerable change in temperature would be necessary to produce any appreciable change in power consumption.

Scrap weight per unit volume varies according to quality. Using heavy scrap a minimum number of furnace recharges is required reducing the total charging time. Scrap quality and the number of charges are interrelated and are not likely to change drastically

between consecutive heats.

Current and impedance type control used in consecutive heats reduced the chance of changes in these variables affecting the overall power-on-time and power consumption figures.

Results

A number of heats were examined to obtain a comparison and the results are shown in Tables 5 and 6.

Impedance type control showed a considerable improvement over current control. Both time and power consumption were reduced in every case checked.

Savings

The results of the tests performed showed that a saving could be achieved using impedance type control. The time saving would result in a 4.85% reduction in labor costs. The cost of furnace power could be reduced by 3.34%.

Figures showing the total labor and power costs for the year were used to calculate the possible saving expected through the use of impedance type control. These figures are based on net ingot tons of steel produced.

TEST NO.	POWER-ON-TIME CURRENT CONTROL (MIN.)	IMPEDANCE CONTROL (MIN.)	TIME SAVING (MIN.)	TOTAL TIME CURRENT CONTROL (MIN.)	IMPEDANCE CONTROL (MIN.)	TIME SAVING (MIN.)
1	152	143	9	215	205	10
2	143	133	10	198	191	7
3	155	140	15	195	185	10
4	166	153	13	230	224	6
5	170	165	5	235	230	5
6	149	143	6	228	212	16
7	132	117	15	200	175	25
TOTAL	1067	994	73	1501	1422	79
AVERAGE	152.4	142	10.4	214.4	203.1	11.3

AVERAGE SAVING = $\frac{73}{1501}$ = 4.85% OF TOTAL TIME

TABLE 5 HEAT TIME - IMPEDANCE TYPE CONTROL VS CURRENT CONTROL

TEST NO.	KWH/TON CHARGED CURRENT CONTROL	KWH/TON CHARGED IMPEDANCE CONTROL	TIME DIFFER-ENCE	KWH/TON CHARGED TO MELT DOWN CURRENT CONTROL	KWH/TON CHARGED TO MELT DOWN IMPEDANCE CONTROL
1	550	531	19	416	384
2	518	485	33	389	390
3	517	507	10	434	429
4	525	509	16		381
5	537	523	14		380
6	510	500	10	403	390
7	522	501	21	413	373
TOTAL	3679	3556	123		
AVERAGE	525.6	508	17.6		

AVERAGE SAVING $= \frac{123}{3679} = 3.34\%$ OF TOTAL POWER

TABLE 6 POWER CONSUMPTION - IMPEDANCE TYPE CONTROL VS CURRENT CONTROL

Average labour cost per ton is \$1.83

Average power cost per ton is \$3.45

Labour saving	1.83 x 0.0485 =	\$0.0886/ton
Power saving	3.45 x 0.0334 =	0.1153/ton
Total saving		\$0.2039/ton

One furnace is capable of producing about 4000 tons of steel per month.

4000 x 0.20 = \$800/month

A saving of \$800 per month could be made in power and labour savings alone through the use of impedance type control on one furnace. The reduction in total heat time is also expected to result in increased production.

Other major costs in the production of steel from electric arc furnaces are electrodes and refractories.

Average electrode cost is approximately \$4.00/ton

Average refractory cost is approximately \$3.00/ton

Since time and power consumption are reduced the thermal and electrical efficiency of the furnace are improved through the use of impedance type control. Any change in electrode consumption is expected to be imperceptible. The average power level is higher and

more constant with impedance type control. This indicates that the average arc length is reduced. Long arcs are very detrimental to the sidewalls since heat is radiated in an almost horizontal direction. Therefore it is anticipated that there will be a decrease in refractory erosion when impedance type control is used in place of current control. An extensive study is required before an estimate of the actual savings in refractory costs and changes in electrode consumption could be made. This would take many weeks since the average refractory life is about two weeks and this should be increased using impedance type control.

CONCLUSION

The electric furnace control circuit was found to be stable under all conditions when the single phase circuit is considered. However, an interaction between phases is present which reduces the stability of the complete three phase system.

The introduction of impedance type control provided a more independent control for each phase resulting in less time and less kilowatt hours required per ton of steel produced. This means a considerable saving in the total cost of the finished material.

Production is expected to increase, resulting in increased revenue. A reduction in refractory wear is expected when impedance type control is used.

Further improvement to the control system may be achieved by repositioning the secondary voltage leads. These could be moved from the transformer secondary bus bars to the electrode holders. Heat resistant shielded leads would be required. The electrode holder voltage signal is much more sensitive to changes in the arc than the transformer secondary voltage presently used.

APPENDIX I

FURNACE SPECIFICATIONS

The electric arc furnace described in this thesis has a shell diameter of 11 feet and a capacity of 20 - 25 tons per heat. The sidewall refractory is made up of 13½ inch bricks while the roof refractory consists of 9 inch bricks. The transformer rating is 8000 KVA with secondary open-circuit voltages ranging from 110 to 266 volts phase-to-phase. The diameter of the graphite electrodes is 12 inches. The flexible conductors from the transformer secondary to the furnace are made up of 12 bare copper cables per phase. The size of each cable is 1750 MCM.

An electro-hydraulic regulator is used with a regulator oil pressure of 60 psi. The hydraulic pressure for raising the electrodes is 300 psi. The hydraulic circuits for roof raising,roof swing, shell tilting and furnace door operation also use a pressure of 300 psi.

The secondary current transformer ratio is 20,000/5. The electrical phase sequence is C-B-A. The phase A electrode is nearest the door and the phase

C electrode is next to the tap hole. (See Figure 6.) The phase B electrode is on the side next to the transformer.

APPENDIX II

MAGNETIC AMPLIFIER

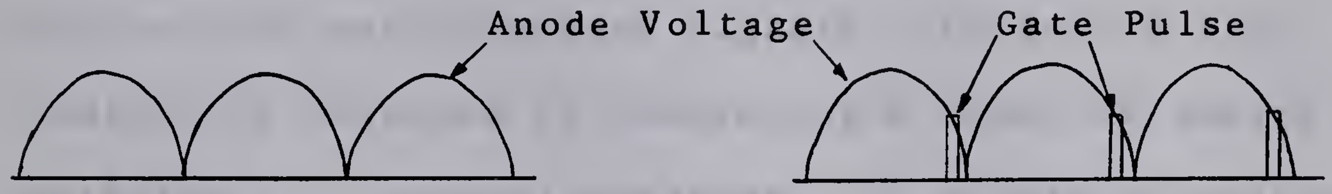
The magnetic amplifier unit used for impedance type control is a Series VS6300, Type A, Bridge Sili-control manufactured by VecTrol Engineering Inc.

It provides a gate drive for a silicon controlled rectifier. Some of the features which make this unit suitable for this application are:

1. One SCR controls a.c. or full wave d.c.
2. It fires any SCR at any temperature.
3. A constant amplitude wide pulse avoids gate overload.
4. It compensates for line voltage fluctuations.
5. It provides linear phase shift of pulse with d.c. control voltage.
6. It has four control windings.
7. It has a temperature range of -40^{o}C to +85^{o}C ambient.

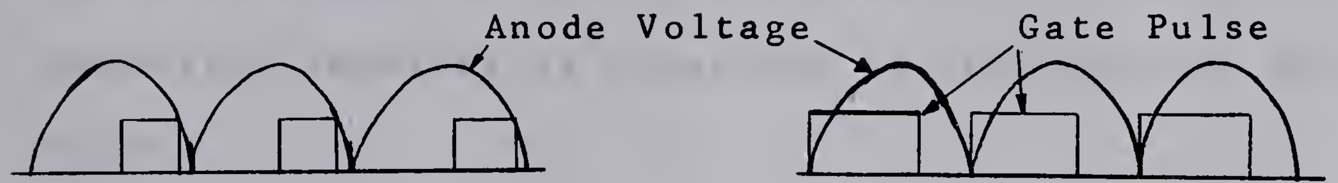
The gate pulse, shown in Figure 37, which appears every 180^{o}, is controlled by a small d.c. signal. The gate current is maintained longer than required to

reach holding current even with a highly inductive load. The regulator coil used for the load in this application is highly inductive.



(a) No Signal Voltage
No Gate Pulse

(b) 5% Signal Voltage
10° Conduction
2% Output



(c) 50% Signal Voltage
90° Conduction
50% Output

(d) 100% or more Signal Voltage
180° Conduction
100% Output

Figure 37 Gate Pulse to Control Conduction Angle of SCR

The SCR can conduct over the full 360° when put in a bridge circuit. The SCR conduction angle is controlled by the resultant ampere turns comprising any arrangement of series or paralleled control windings, either aiding or opposing.

The d.c. control windings are not polarized but the start of each winding is numbered 1, 3, 5, and 7, and must be observed when connecting windings in series

or parallel. In this case the windings are not interconnected but polarized d.c. control is necessary since the voltage signal is opposite in polarity to the current and reference signals. Polarized d.c. control is obtained by connecting a diode in series with the d.c. control windings. To eliminate ripple in the d.c. signal an electrolytic capacitor of 4 to 10 uf is connected across the diode. The positive capacitor terminal is connected to the anode of the diode.

TERMINALS	1 - 2	3 - 4	5 - 6	7 - 8
RESISTANCE (OHMS)	1350	1350	450	450
NO. OF TURNS	3300	3300	1100	1100
CURRENT (ma)	3.3	3.3	10	10
SENSITIVITY	4.5 volts			
(180^{o} SHIFT)	11 ampere turns			
MAXIMUM CURRENT	25 ma			

TABLE 7

NOMINAL CONTROL WINDING RESISTANCES AND D.C. CONTROL CURRENTS AND VOLTAGES FOR 180^{o} PHASE SHIFT.

APPENDIX III

FILTER CIRCUIT

Time constants are introduced by the filter circuits feeding the control windings of the magnetic amplifier. The current and voltage signals must be equal to produce a zero error signal. Figure 38 shows this filter circuit with the control winding of the magnetic amplifier as the load.

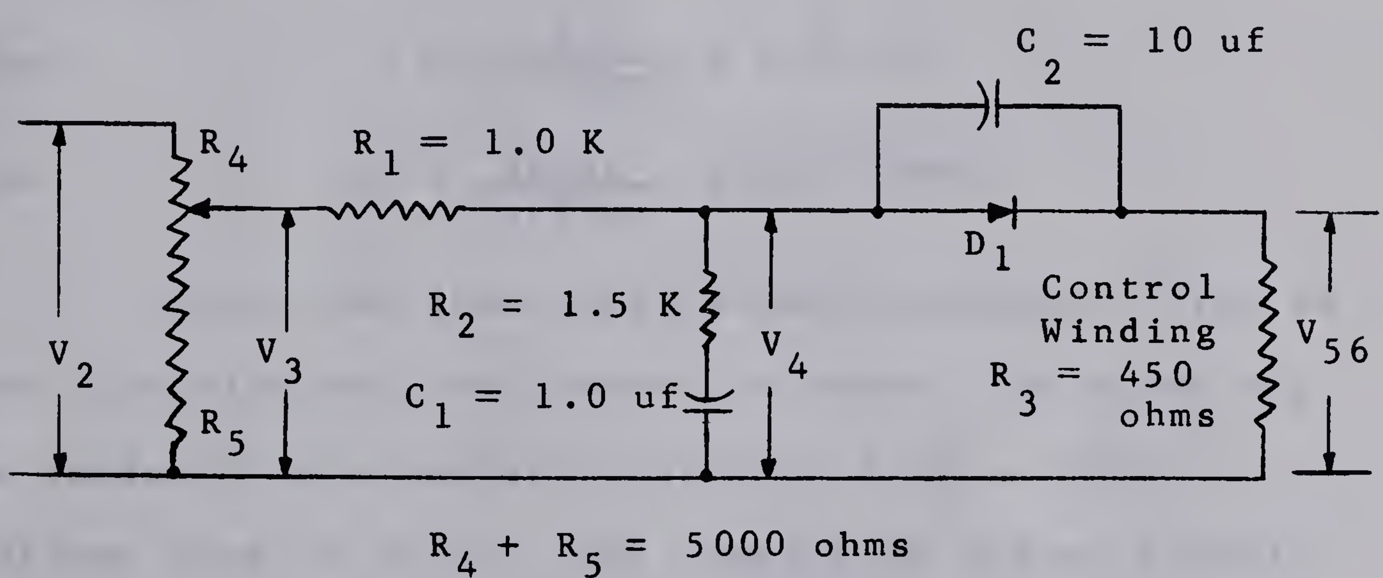


Figure 38 Input Circuit to Magnetic Amplifier

The transfer function can be calculated but the presence of the diode in the circuit makes calculations very difficult unless the following simplification is made.

Forward diode resistance, $R_d = \frac{26\ \text{mv}}{i}$

where 'i' is the current through the diode.

Since the current is d.c. there will be no current through capacitor C_2. Therefore, the current through the control winding is also 'i'.

For zero error signal, the current and voltage signals must supply equal voltages to their respective control windings. This control winding voltage is 1.0 volts.

Then $$i = \frac{1.0\ \text{v}}{450\ \text{ohms}} = 2.22\ \text{ma}$$

and $$R_d = \frac{26\ \text{mv}}{2.22\ \text{ma}} = 11.7\ \text{ohms}$$

Since the diode only allows current to flow in one direction and the current is known, the diode may be replaced by a current source of 2.22 ma with a voltage drop of 26 mv. The simplified filter circuit is shown in figure 39.

$$V_4 = V_{56} + 0.026 = 1.026\ \text{volts}$$

The node equations for the circuit are:

Node 1: $$-V_2 \frac{1}{R_4} + V_3 \left(\frac{1}{R_4} + \frac{1}{R_5} + \frac{1}{R_1}\right) = 0$$

Node 2: $$-V_3 \frac{1}{R_1} + V_4 \left(\frac{1}{R_1} + \frac{1}{R_2 + \frac{1}{C_1 S}}\right) + 2.22 \times 10^{-3} = 0$$

Then $$\frac{V_2}{R_4} = V_3\left(\frac{R_4 + R_5}{R_4R_5} + \frac{1}{R_1}\right) = V_3\left(\frac{5000\ R_1 + R_4R_5}{R_1R_4R_5}\right)$$

$$\frac{V_3}{V_2} = \frac{R_1R_5}{5000\ R_1 + R_4R_5}$$

$$R_1 = 1.0\ K$$

$$\frac{V_3}{V_2} = \frac{R_5 \times 10^3}{5.0 \times 10^6 + R_4R_5}$$

and $$\frac{V_3}{R_1} = V_4\left(\frac{1 + R_2C_1S + R_1C_1S}{R_1\ (R_2C_1S + 1)}\right) + 2.22 \times 10^{-3}$$

$$R_2 = 1.5\ K \quad R_1 = 1.0K \quad C_1 = 1\ uf$$

$$V_3 = V_4\left(\frac{1 + 2.5 \times 10^{-3}S}{1 + 1.5 \times 10^{-3}S}\right) + 2.22$$

$$\frac{V_3}{V_4} = \frac{1 + 2.5 \times 10^{-3}S}{1 + 1.5 \times 10^{-3}S} + \frac{2.22}{V_4}$$

$$V_4 = 1.026 \text{ volts}$$

$$\frac{V_3}{V_4} = \frac{1 + 2.5 \times 10^{-3}S}{1 + 1.5 \times 10^{-3}S} + \frac{2.22}{1.026}$$

$$= \frac{1 + 2.5 \times 10^{-3}S + 2.16 + 3.24 \times 10^{-3}S}{1 + 1.5 \times 10^{-3}S}$$

$$\frac{V_3}{V_4} = 3.16\left(\frac{1 + 1.82 \times 10^{-3}S}{1 + 1.5 \times 10^{-3}S}\right)$$

$$\frac{V_4}{V_3} = \frac{1}{3.16}\left(\frac{1 + 1.5 \times 10^{-3}S}{1 + 1.82 \times 10^{-3}S}\right)$$

Let $$K = \frac{R_5 \times 10^3}{5 \times 10^6 + R_4 R_5}$$

Then $$V_3 = V_2 K$$

$$\frac{V_4}{V_2} = \frac{K}{3.16} \left(\frac{1 + 1.5 \times 10^{-3} s}{1 + 1.82 \times 10^{-3} s} \right)$$

$$V_{56} = V_4 - 0.026$$

$$V_{56} \approx V_4$$

The error introduced by this approximation is negligible. The transfer function of the filter circuit is

$$G = \frac{V_{56}}{V_2} = \frac{K}{3.16} \left(\frac{1 + 1.5 \times 10^{-3} s}{1 + 1.82 \times 10^{-3} s} \right)$$

'K' varies as the potentiometer resistance is changed.

The time constants for this portion of the control circuit are much smaller than those found from the tests on the regulator response. Therefore, they should have little effect on the regulator response and the transfer function may be approximated by the equation:

$$G = \frac{V_{56}}{V_2} = \frac{K}{3.16}$$

where $$K = \frac{R_5 \times 10^3}{5 \times 10^6 + R_4 R_5}$$

and $$V_4 = \frac{V_3}{3.16}$$

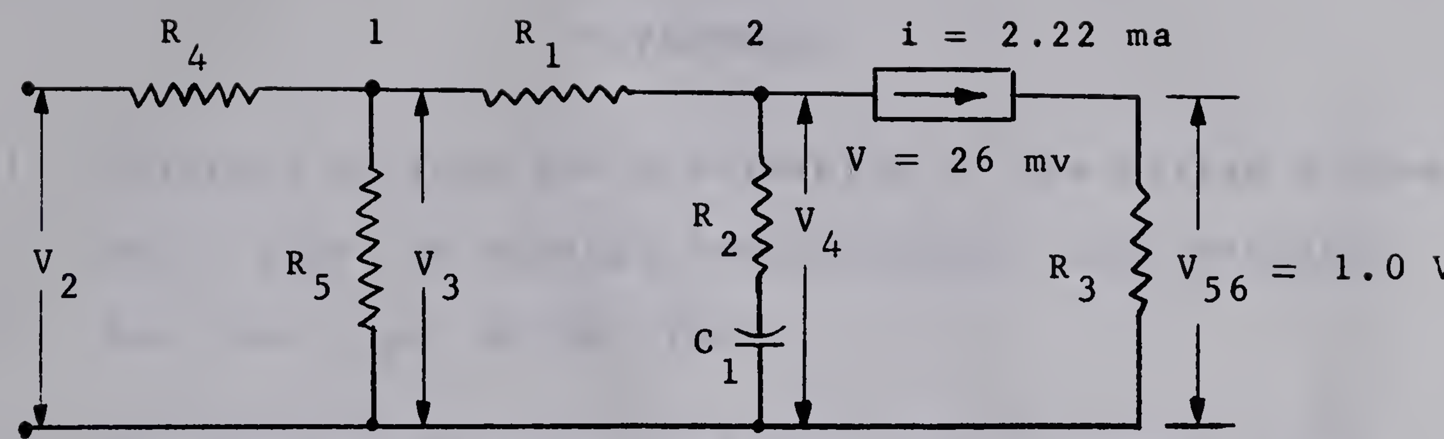


Figure 39 Simplified Filter Circuit

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